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DEVELOPMENT of a PREDICTIVE MODEL to ASSESS the EFFECTS of EXTENDED SEASON NAVIGATION on GREAT LAKES CONNECTING WATERS

FINAL REPORT

Michigan Technological University

Houghton, Michigan

October 1986

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The object of this study was to develop a method for forecasting the physical effects of the passage of commercial vessels through Great Lakes connecting waters during that period of time when traffic is normally at a minimum due to a more or less continuous ice cover. The physical impacts examined were sediment translocation, water quality effects, direct damage to existing structures, and changes in the gross hydraulic regime. Also associated with the report but bound separately are; the User's Manual for Prediction of Vessel Impacts in a Confined Waterway; Appendix A, Site and Soil Conditions; Appendix B, Observed Vessel Induced Water Level Drawdowns; and Appendix C, Observed Ice Thicknesses and Water Turbidities.

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TO ASSESS THE EFFECTS OF EXTENDED SEASON NAVIGATION
ON GREAT LAKES CONNECTING WATERS

FINAL REPORT

by Ralph J. Hodek
Michael D. Annable
George R. Alger
Henry S. Santeford

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INTRODUCTION

The objective of this study was to develop a method for forecasting the physical effects of the passage of commercial vessels through Great Lakes connecting waters during that period of time when traffic is normally at a minimum due to a more or less continuous ice cover.

The physical impacts examined were sediment translocation, water quality effects, direct damage to existing structures, and changes in the gross hydraulic regime. The analysis has been conducted by utilizing information collected in previous years during the Winter Navigation Demonstration Program, data which was gathered during the twelve-month period of this study, and analytical techniques which were modified or developed for this particular effort.

The findings were developed for the St. Marys River system specifically, but are of general applicability for the range of vessel configurations, operational characteristics, and system hydraulic characteristics regardless of geographic location.

All field data collected during this study, as well as selected data from previous studies, are contained in Appendix A--Site and Soil Characteristics, Appendix B--Observed Vessel-Induced Water Level Drawdowns, and Appendix C--Observed Ice Thicknesses and Water Turbidities, which are bound separately. Also included as a part of this report, and bound separately, is the User's Manual for Prediction of Vessel Impacts in a Confined Waterway, which supports the computer program developed for this study.

Plate 1, located in the map pocket of this volume, shows the St. Marys River and surrounding features. The particular study locations are described later in this report.

ST. MARYS RIVER HYDRAULICS

River velocities in the St. Marys River system are affected by the total discharge to the river from Lake Superior, the division of this flow around Sugar Island and around Neebish Island, and the level of Lake Huron. From what limited information is available it appears that the division of flow around the islands has been altered from time to time as improvements have been made on the navigation channels. These flow divisions would also likely be altered due to large accumulations of brash ice, at varying locations, which have developed due to vessel passages through the ice. For the purpose of this study the findings discussed in the internal Detroit District Corps of Engineers report, "Analysis of 1965 Discharge Measurement on the St. Marys River," will be used to estimate flow divisions.

The average discharge in the St. Marys River is about 74,500 cfs with maximum monthly flows as high as 133,000 cfs and as low as 41,000 cfs. The swiftest currents in the navigable channels are found at the Middle Neebish Channel dike, West Neebish (Rock Cut), and Little Rapids Cut. The actual values are dependent on the discharge from Lake Superior, the Lake Huron stage, and the flow division around Sugar Island and Neebish Island. In the ice free periods the flow from Lake Superior is split with approximately 25% to the St. George Channel and 75% to Little Rapids Cut and further divided at Neebish Island with about 35% passing through Rock Cut.

There is some evidence (Corps of Engineers internal document, "St. Marys Discharge and Flow Distribution Measurements 1965-1979") to suggest that the flow division around Sugar Island was altered during the months of February 1972, 1973, and 1976 to

65-70% split to Little Rapids Cut. It is possible that river ice conditions in the navigable portion of the system may have shunted more of the outflow from Lake Superior to the St. George Channel.

The model proposed for predicting "drawdown" uses average river velocity as part of the input. These values may be reasonably estimated at the impact sites using the outflow from Lake Superior, the division of flow discussed above, river water level, and river cross-section.

AREA GEOLOGY AND SOIL CONDITIONS

The geology surrounding the St. Marys River can be divided into two categories, the bedrock of the Michigan Basin, and the Pleistocene deposits overlaying the bedrock.

The St. Marys River flows southeast through the northern arch of the Michigan Basin. The beds in this area trend approximately east-west and dip slightly to the south. The river therefore flows over younger beds as it flows south to Lake Huron. The bedrock in and around the Sault Ste. Marie area consists of Cambrian deposits. These deposits extend south to near the southern end of Sugar Island. Cambrian deposits consist predominantly of fine to medium grained sandstones. South of Sugar Island extending to the north shore of Drummond Island the bedrock consists of Ordovician deposits which are carbonates and shales. In this area limestones are dominant. South of the north shore of Drummond Island into Lake Huron the bedrock consists of Silurian deposits. Carbonates make up the majority of the Silurian deposits, one formation being the very resistant Niagarian Dolomite. Both the Ordovician and Silurian deposits are very fossiliferous and attain a thickness of 1,700 feet.

The area surrounding the St. Marys River is overlain by glacial deposits up to 200 feet thick. Only in the southern reach near Lake Huron and at Rock Cut does the bedrock outcrop at the surface. However, only very thin deposits are found on Neebish Island and the southern end of Sugar Island. The Pleistocene deposits consist dominantly of lake bed (lacustrine) deposits of sand and clay. The sand deposits tend to be located predominantly in a band following the shore of the St. Marys River. Further inland lake bed clays are dominant. Other glacial features found

in the area include low lying moraines which were deposited in water or later covered by glacial lakes. The moraines can be found on the mainland as well as Sugar Island.

The area of interest for this study extends from the St. Marys Canal to Lake Munuscong, this being the area which contains channels which are both narrow and relatively shallow. The drainage basin for this area is quite small and the upland drainage pattern is poorly developed. The only perennial streams which enter the navigation channel are located on the U.S. mainland. Ermatinger Creek which is located between Frechette Point and Six Mile Point contributes sand to the St. Marys River as evidenced by its creek-mouth bar and strong bed ripple pattern, but due to its negligible drainage area the annual sand contribution is small and only important for a short distance downstream on the St. Marys. The Charlotte River across from Sand Island in the West Neebish Channel has the greatest flow and the largest drainage area as well. During this study it appeared that the Charlotte River's mineral contribution to the St. Marys was largely in the silt and clay size range, although fine sand sized material is available on the bed in the lower reach of the Charlotte River and would conceivably move into the St. Marys at lower Lake Huron lake levels. The other creeks are not considered to contribute a significant mineral load to the St. Marys River. The drainage basin soils in the area of interest are typified by the Rudyard and Munuscong series. The Munuscong series is confined to the lower elevations near the river and is composed of a few feet of loamy sand to sandy loam overlying plastic clay. The Rudyard series is a silty clay loam to silty clay and occupies the upland areas of the basins. It is estimated that the Rudyard series adequately describes over 80% of the surface soil in the area of interest.

It is judged that there is no significant sediment transport into the system at the locks, control structure, or the power canals. Therefore, for the most part, sediment accretion or shoaling at some point in this area is directly related to channel slumping, nearshore deepening, beach recession, or bluff recession at some upstream point in this same area. The average annual sediment contribution from the drainage basin could not be accurately determined. However, it is judged to be modest and more apparent than real since the majority of the sediment is fine-grained. This fine-grained soil, in small quantities, will cause significant turbidity and may move a considerable distance downstream before settling to the bottom. Channel slumping, nearshore deepening, and beach recession involves the translocation of predominantly granular soil of sand size, while bluff recession can provide the full spectrum of soil particle sizes.

OBSERVATION SITES--SELECTION AND CHARACTERISTICS

Seven sites were chosen as locations at which vessel-induced water level changes would be recorded and at which sediment movement patterns would be measured during vessel passages. The sites were chosen to represent a wide range of channel areas and cross-section configurations, and a wide range of nearshore soil conditions. Two of the sites, River View and Nine Mile, had been used for previous studies.

The chosen site locations are shown in Figures 1, 2, and 3. General comments about each site are given below. Site details such as the exact location and orientation, bathymetric cross-section and sounding data, and soil grain-size characteristics, are given in Appendix A--Site and Soil Conditions.

River View

This site is located in the two-way channel just upstream of the mouth of Frechette Creek. The green side bank is rip-rapped and the nearshore bed is a silty fine sand. Throughout this report locations will be referred to as "green side" or "red side". This convention was adopted from the buoyage convention used on the Great Lakes that dictates that red navigation aids are on the right-hand side of the channel when one is proceeding upstream or toward the head of navigation. River View's red side nearshore bottom is composed of intact highly plastic clay, occasional very thin accumulations of fine sand, and scattered lumps of highly plastic clay up to one foot in "diameter." No beach was present at the 1985 water level and the river impinges directly on a clay bluff about four feet high. The speed limits at this site are 8 mph (11.7 fps) upbound and 10 mph (14.7 fps) downbound.

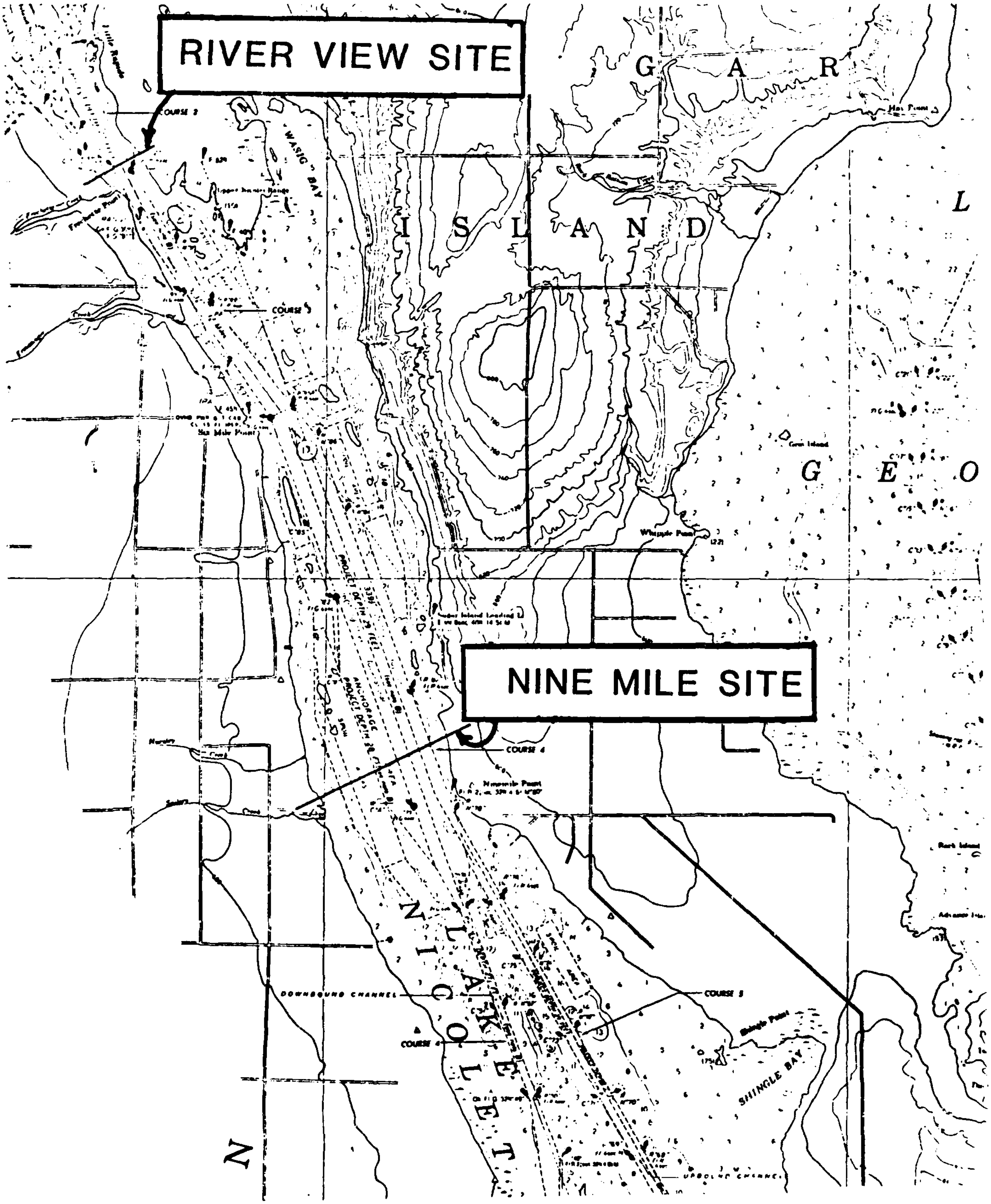

Figure 1. Site Locations in the Northern Portion of the Study Area

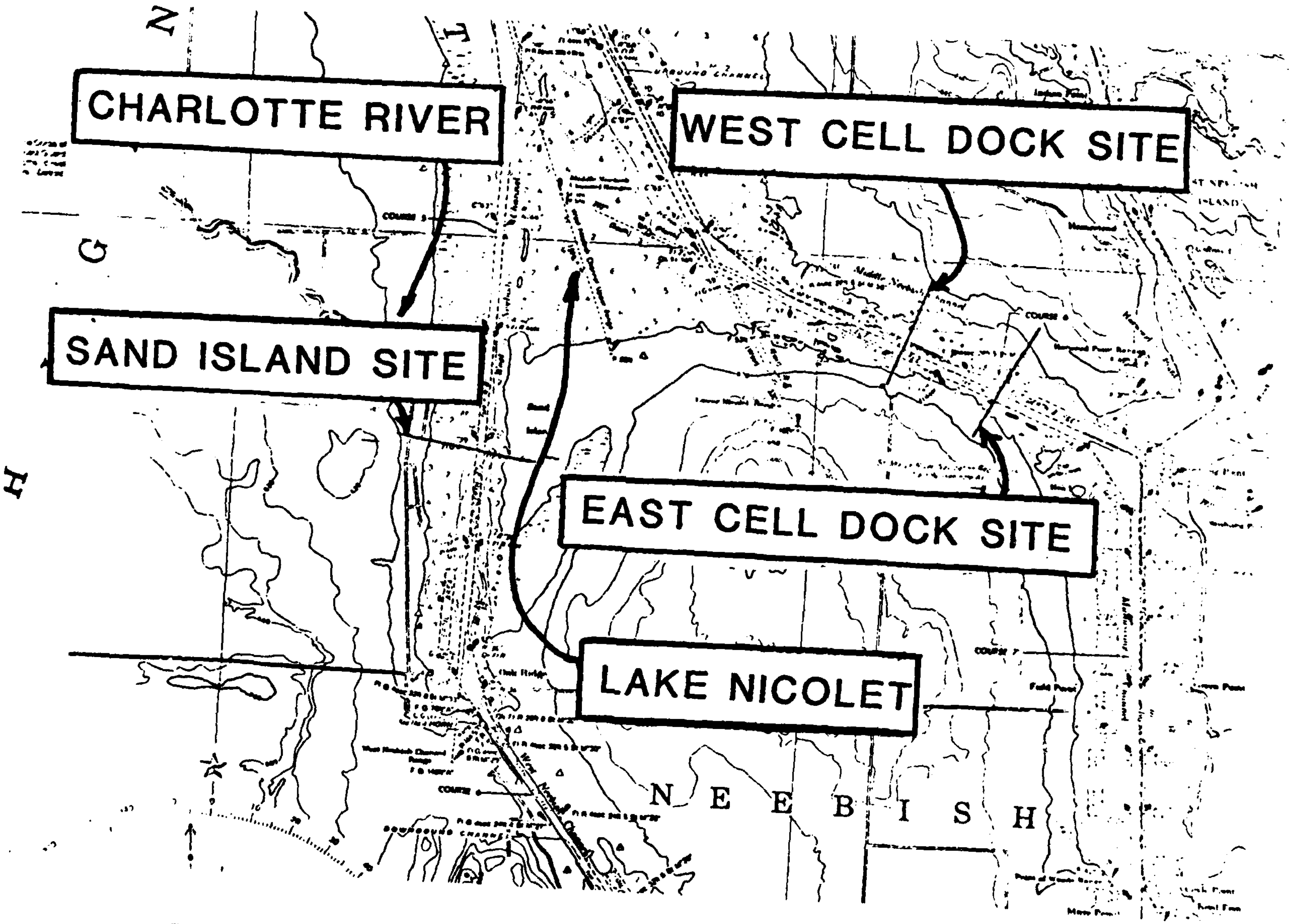

Figure 2. Site Locations in the Central Portion of the Study Area

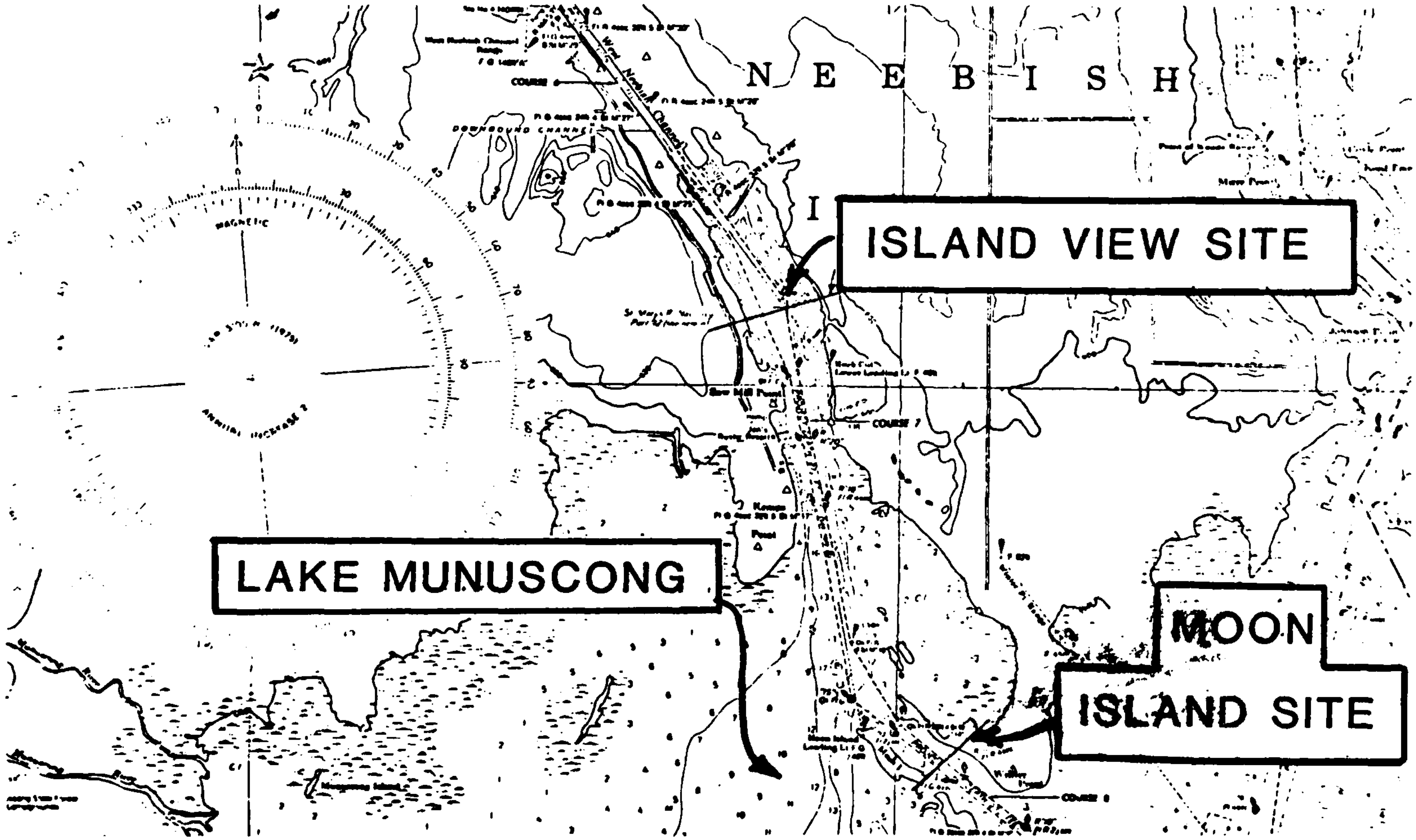

Figure 3. Site Locations in the Southern Portion of the Study Area

Nine Mile

This site is located in the two-way channel just above Sugar Island's Nine Mile Point. It has a very wide channel and very large total cross-section. The bank-to-bank distance is more than 5,600 feet. The green side nearshore is an aquatic bed with a bottom of amorphous granular and fibrous non-woody peat. The red side shore has been rip-rapped and the near-shore bottom is a plastic clay covered by a more or less continuous layer of fine sand. The sand thickness is only a few inches at the shoreline and appears to thicken in the offshore direction. The speed limit at this site is 10 mph (14.7 fps) in both directions. Observed vessel effects on the green side were negligible.

Sand Island

This site is located in the downbound West Neebish Channel approximately one-half mile below the mouth of the Charlotte River. The green side nearshore bottom is silty fine sand with a trace of organic material, and the shore is a low bank which is heavily vegetated. Moving offshore on the green side the soil quickly grades to a sandy silt. On the red side the shoreline is composed of a sandy beach, a low sand berm, and a broad sand backbeach. Both the nearshore bed and the beach are fine sand with only a trace of silt. The speed limit is 10 mph (14.7 fps) downbound. Observed vessel effects on the red side were quite dramatic on occasion.

Island View

This site is located on a turn between Rock Cut and Saw Mill Point in the downbound West Neebish Channel. The green side shoreline is a low grassy bluff and the nearshore bed is a fine sand to silty fine sand. The red side shore is a steep gravel beach, and its nearshore bed is fine sand to silty fine sand. Vessel effects at this site were quite variable, possibly due to variable vessel distances offshore in the turn. The speed limit is 10 mph (14.7 fps) downbound.

Moon Island

This site is located at Moon Island in the downbound channel just above Winter Point at the entrance to Lake Munuscong. The red side shore and backshore are at the 1985 river level and are completely vegetated by marsh grass and rushes. The red side near- shore bed is an intact clay of low plasticity. The green side shore is Moon Island which appears to be a dredge spoil pile. The nearshore terminates in a clay bluff three to four feet high. The nearshore soil is a clay of low plasticity which becomes more plastic in the offshore direction. The Moon Island bluff has noticeably eroded during the period of this study. The speed limit at this site is 10 mph (14.7 fps).

East Cell Dock

This site is located in the upbound Middle Neebish Channel about 1 1/4 miles above Stribling Point. This site was chosen be-cause of the channel's nearness to the green bank and coarse soil composition on the green side. However, the shoreline shape on

the red side as well as the beginning of a limestone spoil revetment a short distance upstream caused very irregular water level fluctuations during vessel passages. For this reason the site was given a low priority and seldom observed.

West Cell Dock

This site is located in the upbound Middle Neebish Channel about three quarters of a mile upstream of the East Cell Dock site. The channel appears to have required considerable rock excavation as the red side "shore" consists of an almost continuous narrow low island of limestone spoil adjacent to the channel. The red side nearshore deepens quite rapidly and is composed of limestone fragments and cobbles. The green side nearshore is primarily fine to medium sand with occasional gravel. There is a noticeable absence of silt or clay-size material. The green side shore is a low bluff which is well vegetated with grasses and low woody shrubs. The up-bound speed limit is 10 mph (14.7 fps).

ANALYTICAL PREDICTION OF VESSEL-INDUCED WATER LEVEL DRAWDOWN

It has been recognized for some time that a) a vessel passing through a narrow channel acts as a constriction in the channel and thus causes a water level drop, or drawdown, in the channel adjacent to the vessel, and b) the nearshore water velocities are altered in both magnitude and direction.

The direct effect of temporary water level change as it affects structures in the presence of a floating ice cover and as it affects the beach or bluff area above the ambient water line dictates that the vessel-induced water level change must be understood to facilitate forecasting. The secondary effect of this drawdown, the induced nearshore water velocity pattern, may cause bottom disturbances; and as it is related to the drawdown, this source of secondary damage cause may also be understood from the drawdown predictions.

The requirements of this drawdown prediction model are a) the ability to adequately predict the magnitude of vessel-induced drawdown, b) rapid computation, c) the flexibility to easily incorporate the system variables in an interactive manner, and d) the ability to provide the computational results in an easily understood format.

The following sections explain the development of a computerized mathematical model to predict drawdown and to demonstrate the effects of common variables. The development is based in simple hydraulic principles and has previously been applied to similar situations (3, 12). The features and use of the resulting computer program are explained in a separate volume of this report

entitled "User's Manual - Prediction of Vessel Impacts in a Confined Water-way."

Theoretical Basis of the Model

The basic structure of the model which is used to compute drawdown due to vessel passage is formed by simultaneous solutions of the steady state continuity equation ($Q = AV$) and a steady state energy equation:

$$Y_1 + \frac{V_1^2}{2_g} = Y_2 + \frac{V_2^2}{2_g}$$

where: Q = flow rate (cfs)
A = appropriate cross-section area of flow (ft^2)
V = velocity (fps))
Y = depth.
g = gravitational acceleration

In order to apply the above steady state relations, the physical situation (one of unsteady flow) must be conceptually converted to a steady state case. This is conveniently accomplished by conceptually stopping the vessel (adding a velocity vector equal to the vessel speed but of opposite direction to all components of the system). Thus different magnitudes of drawdown will be computed for the same vessel and vessel speed depending on vessel direction, up river or down river (smallest drawdown for the down river direction). It is assumed that energy losses will be small, that there is not cross-over flow beneath the vessel and that the flow is proportioned to each side of the vessel in proportion to the areas available for flow on each side of the vessel. In the vast majority of "real" situations these are reasonable assumptions as reported by Constantine (5), Sorensen (13), McNown (8), and Wuebben (15).

It is possible, in small river cross-sections with large vessels moving at great speed, for the model to reach its limit (so-called "critical conditions"). At this point a re-evaluation of the basic energy statement would be required with consideration for increased river levels forward of the vessel's bow. This can theoretically be accomplished in mathematical form; however, it would require at least the above assumptions (not likely to be met at this extreme). Further, the damage potential would already be very great at this point. It was therefore felt that such further refinement to accommodate such a possibility was not justified and that model output would only be that which would advise the user of such a "critical" state (see page 46 of the User's Manual). This situation may be visualized with reference to pages 70-75 of the User's Manual where the figures illustrate how drawdown increases with vessel speed and at high speeds the computed drawdown increases greatly with only a small increase in the vessel speed (the situation is approaching "critical").

All other things being equal the presence of ice would decrease the area available for flow (for a given water level), and computed drawdown would increase. The model will accommodate this condition; however, the assumptions mentioned above are still in place. Certainly some energy would be utilized in flexure of the ice cover, ice translocations and ice fracture, and this cannot be presently accounted for in a realistic manner. However, it is felt that the mitigating effect of an ice cover would be slight in channels with a small bank-to-bank dimension in comparison to those channels which are relatively wide bank-to-bank since the wider section provides a longer ice cover dimension perpendicular to the vessel's direction of travel, and the entire dimension is available for energy dissipation.

It should also be noted, especially with larger vessel speeds, that vessel draft, vessel speed and vessel location will have great influence on computed drawdown. They must be accurately represented, therefore, in order to obtain reliable computed values of drawdown.

Effects of Common Variables

In an effort to provide a mathematical model which can be used without the need for extensive field data collection, the input requirements have been held to those which in many cases can be secured from navigation charts, office records, general site knowledge, and ambient water level projections. This section examines the sensitivity of several of these variables to the result. It is by no means exhaustive, and the user is cautioned that changing combinations of variables may significantly alter the result. The results shown were determined directly by the computer program although not all of the figures can be displayed in the format shown directly from the computer program.

The theory upon which the analyses are based does not consider the vessel's waterline length when predicting the water level change. This is in agreement with Wuebben et al (16) who feel that vessel length is unimportant.

Variable Ice Cover Thickness. To demonstrate the effect of ice cover thickness, the passages of upbound and downbound vessels at the Riverview site were simulated. The following constants were used. The vessel was at the approximate channel center regardless of passage direction, river velocity was 1.4 fps, each vessel had a beam of 105 feet and a draft of 27 feet, and vessel speed was 11.0 fps in both directions. Note that the published

speed limit in the <u>United States Coast Pilot</u>, Vol. 6, is 8 mph (11.7 fps) upbound and 10 mph (14.7 fps) downbound.

Figure 4 shows the predicted water level changes as a function of ice thickness for the green side and red side shores for both upbound and downbound vessels. For the variables considered, the maximum drawdown ratio (ice covered/ice free) varies from 1.15 to 1.33 with the greatest influence being caused on the red side by an upbound vessel.

<u>Variable River Velocity</u>. The effect of river velocity is shown in Figure 5. This figure uses the River View site, assumes that travel is downbound and is offset 100 feet to the green side of the channel centerline, assumes zero ice cover, uses a vessel speed of 12.5 fps, and examines both a lightly ballasted, relatively small vessel and a fully loaded, large vessel.

Although the effect of river velocity on vessel-induced drawdown is an important variable, Figure 5 suggests that an approximation of the correct river velocity may be sufficient and that field measurements may not be justified.

<u>Vessel Position in Relation to Channel Centerline</u>. It has been observed that the position of a vessel within the confines of the navigation channel cross-section is not constant. The effect of vessel location within the cross-section is shown for the River View site in Figure 6. The upbound vessel is traveling at a velocity of 11.7 fps (the legal limit), has a beam of 105 feet, and is drawing 21 feet. This is a reasonable draft for large vessels in ballast. The downbound vessel has a velocity of 14.7 fps (also the legal limit), a 105 foot beam, a fully loaded draft of 27 feet, the river velocity is 1.4 fps, and ice is absent. Note that the channel centerline is approximately 900 feet from the green

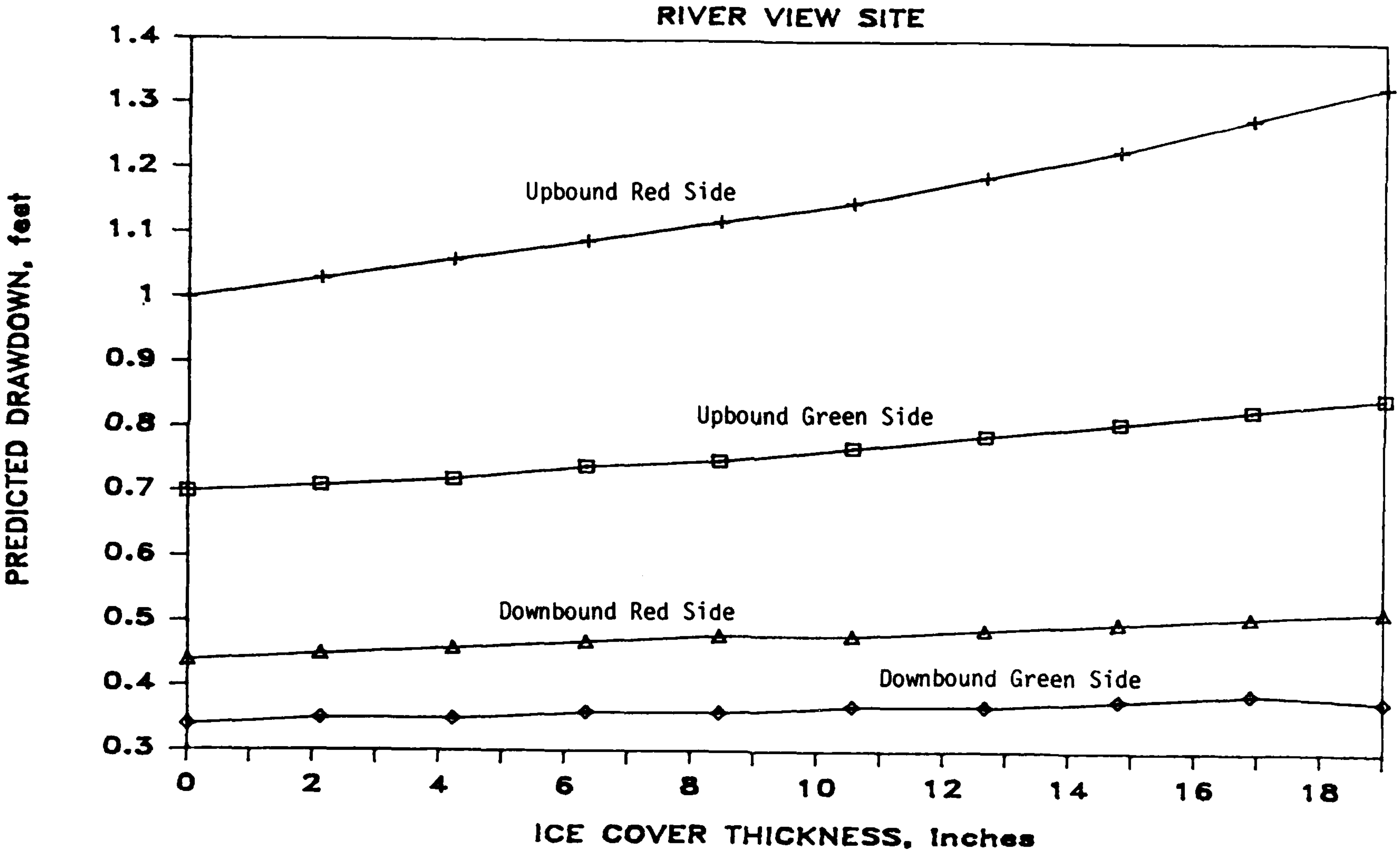

Figure 4. Effect of Ice Cover Thickness on Predicted Drawdown

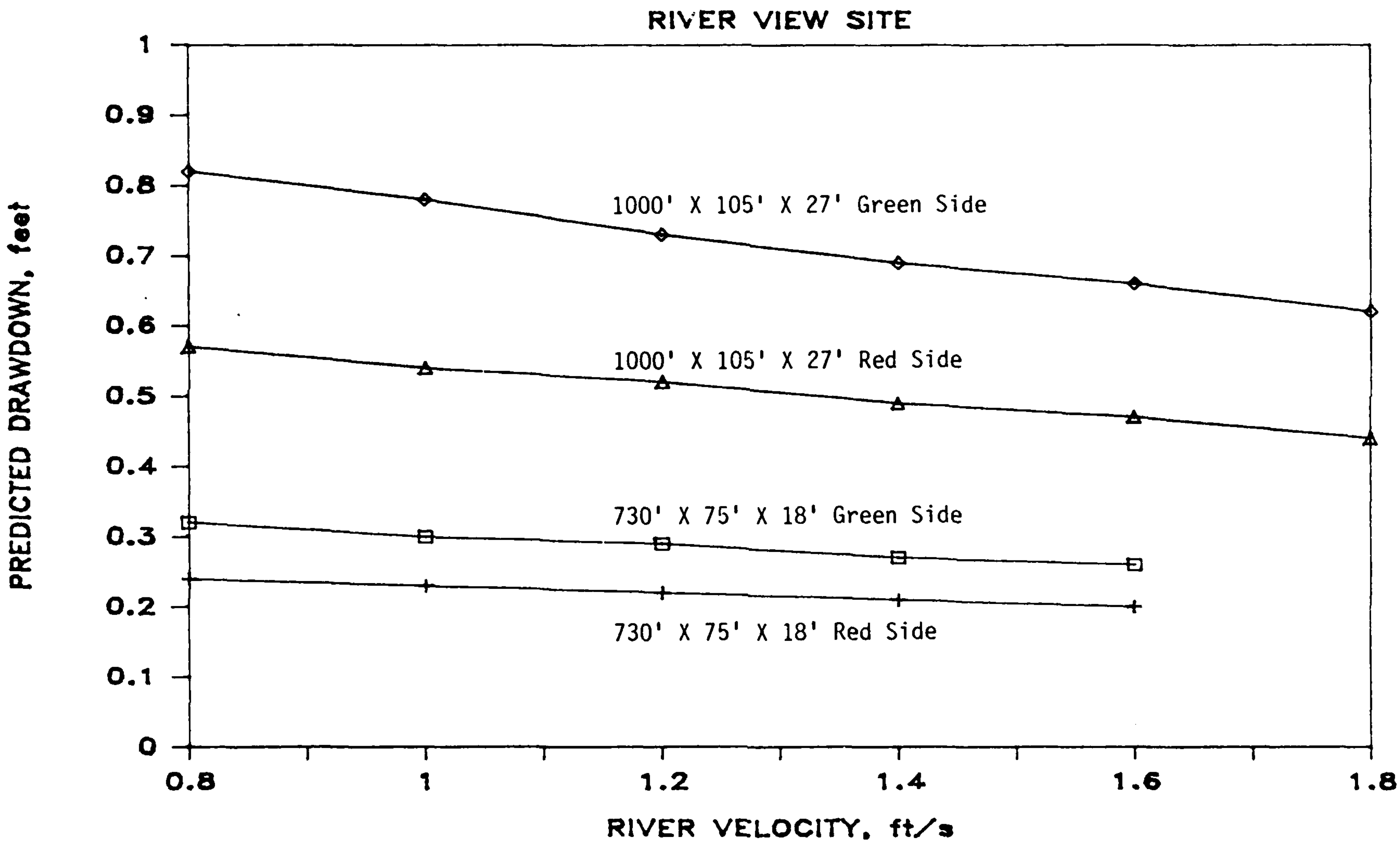

Figure 5. Effect of River Velocity on Predicted Drawdown

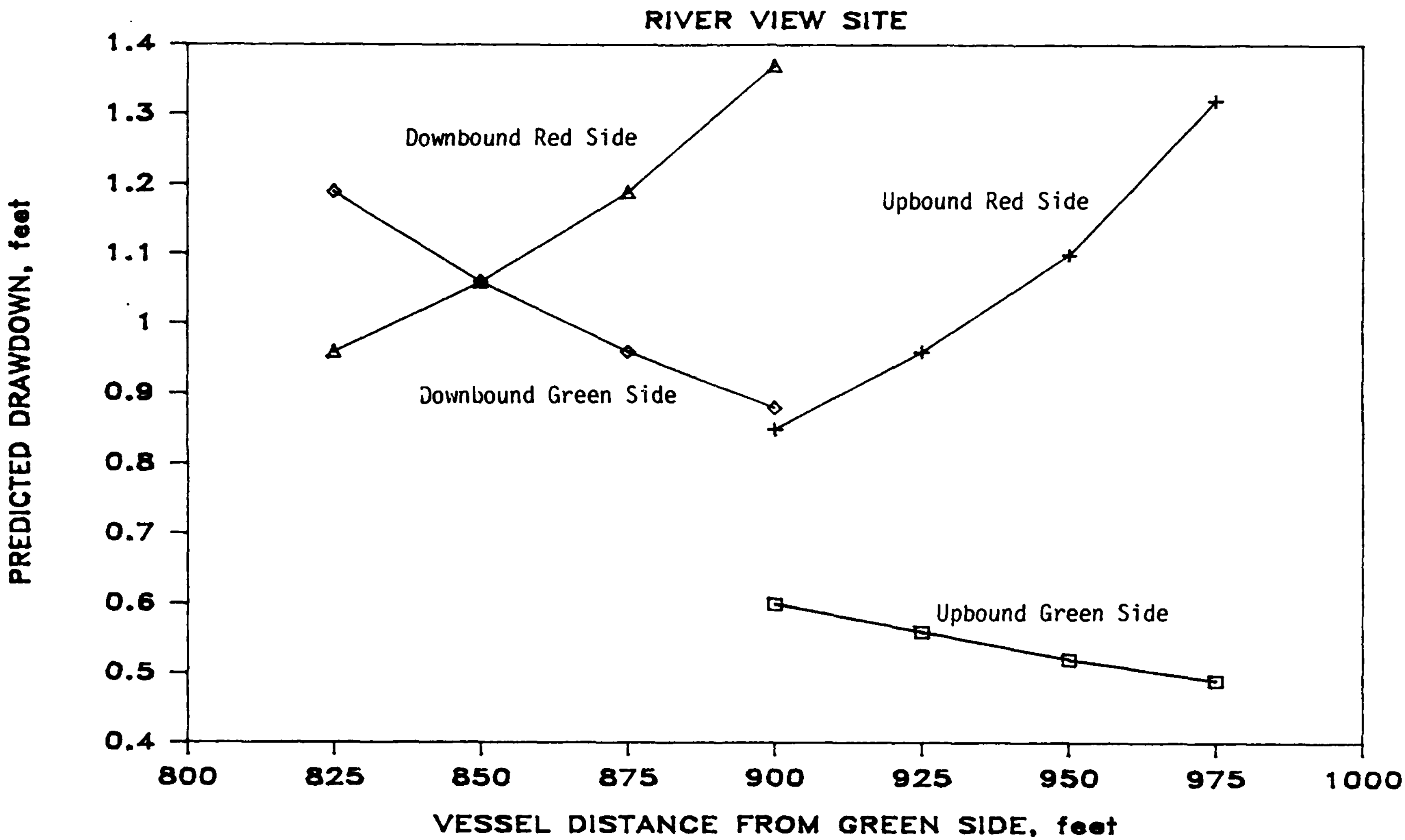

Figure 6. Effect of Vessel Position in Channel on the Predicted Drawdown

side. The results show that nearshore drawdown is predicted to be very dependent on the position of the vessel. It is indicated that for the upbound vessel moving shoreward from the channel center, only 75 feet increases the predicted drawdown by 55%, from 0.85 feet to 1.32 feet.

It should be noted that the accumulation of very thick brash ice in the track, as the winter season progresses, may result in the decision to develop a new track adjacent to the clogged one. The effect of this will be to move vessel passages away from the channel centerline thus increasing the drawdown on one side while decreasing it at the other.

Vessel Speed. The final variable to be demonstrated is vessel speed. Again the analysis will be made at the River View cross-section. Ice is absent and a large ballasted upbound vessel and large fully loaded downbound vessel are assumed. Both vessels are assumed to be traveling on the channel centerline. Figures 7 and 8 show the computed relationships for upbound and downbound vessels, respectively.

Since the resulting drawdown is so dependent on vessel speed, and since speeds high enough to cause relatively large drawdowns in the presence of moderate ice conditions are possible, the presence of effective speed regulation at sensitive locations may be of primary importance.

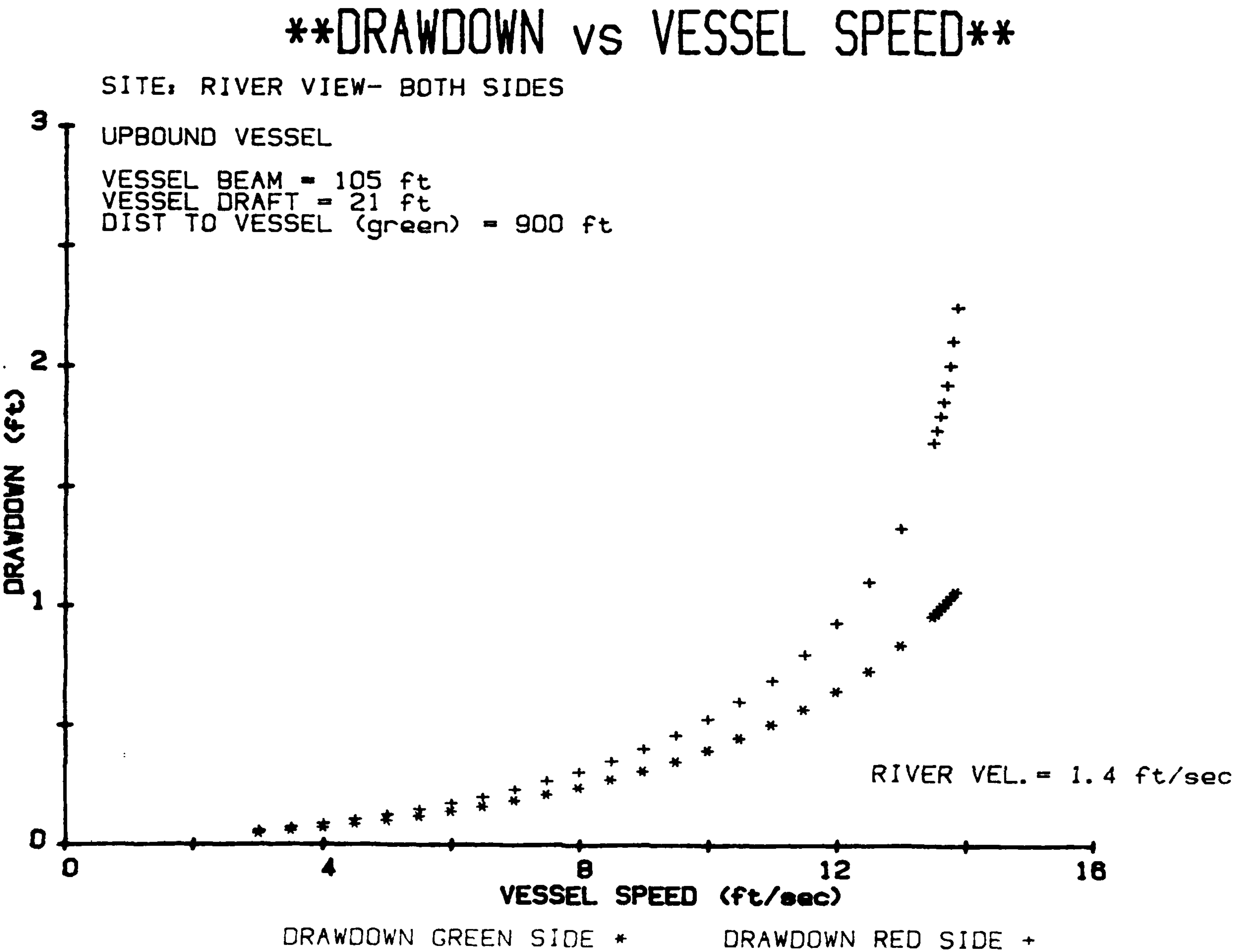

Figure 7. Effect of Upbound Vessel Speed on Predicted Drawdown

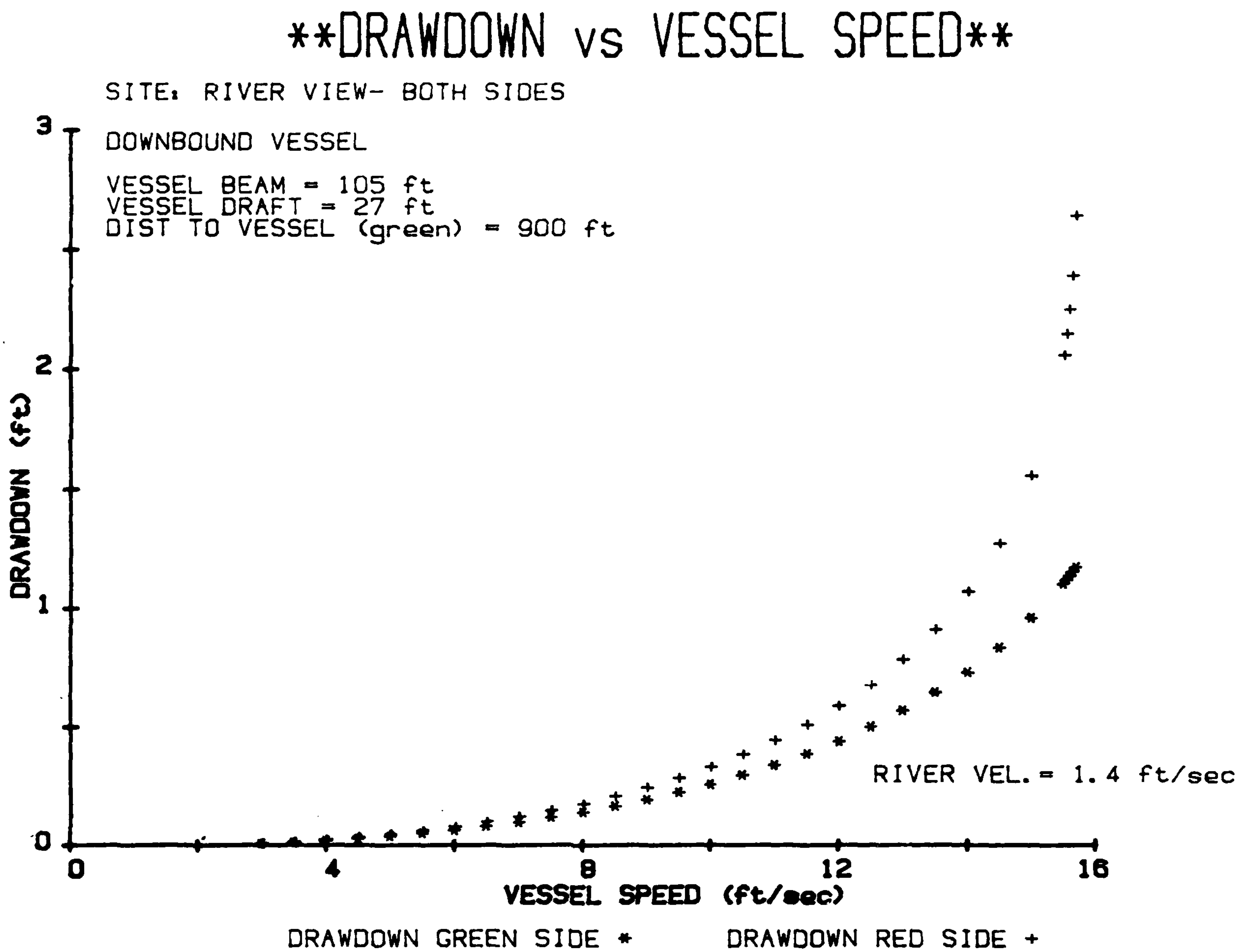

Figure 8. Effect of Downbound Vessel Speed on Predicted Drawdown

A COMPARISON OF PREDICTED AND OBSERVED WATER LEVEL CHANGES

As part of this contract a considerable effort was expended in gathering data sets of the vessel-induced water level vs. time relationship to aid in the development and validation of the predictive model. Due to the extremely high water level of the St. Marys River during the 1985 study period, the range of vessel speeds was not as wide as was desired. This was due to the fact that vessel speed limits were lowered and effectively enforced by the U.S. Coast Guard in the most damage prone areas. These areas coincided with the ones chosen as observation or study sites for this project. This section briefly describes the observational procedure, the drawdown results obtained, and analyzes the model predictions in the light of these results.

Observational Procedure

On any given day a particular site was chosen for observation based on the weather forecast (high waves hinder the measuring process), the anticipated vessel volume and direction, and the results of previous observations.

Drawdown measurements were made directly by recording the staff gauge readings simultaneously in the nearshore zones on the red and green sides of the site's cross-section line. This was accomplished by transmitting a time count by radio which was picked up on the tape recorders being used by both staff gauge observers who were entering their own data onto the same tapes. The time broadcaster and a fourth crew member were responsible for determining and recording vessel speed and draft, and miscellaneous observations concerning the start of sediment motion

and the characteristics on any surge following the water level drawdown.

Results

A total of 97 vessel passages were quantitatively monitored during this study. The drawdown vs. time records for these, as well as the records for six vessels monitored in 1977 and 1979, are contained in Appendix B, a separate volume of this report. A typical data set is reproduced here as Figure 9. The relevant vessel characteristics pertaining to each passage are also given in Appendix B.

Originally the East Cell Dock site was considered as being an appropriate upbound observation site. However, after three vessel passages the site was abandoned due to the atypical pattern of water level fluctuation. This abnormal pattern was probably due to the cove-like shoreline shape which enhanced water level oscillation.

Analysis

The usefulness of the model prediction depends in part on its accuracy in predicting the magnitude of drawdown. To assess this, the maximum drawdown was computed for each set of useable data and compared to the actual measured drawdown. Useable data are those which represent nearshore drawdowns at locations with known cross-sections.

Figure 10 shows the result of this comparison as a function of predicted drawdown for downbound vessels. The tolerance interval wherein one is 95% confident that errors will be within these bounds 90% of the time based on a normal distribution is

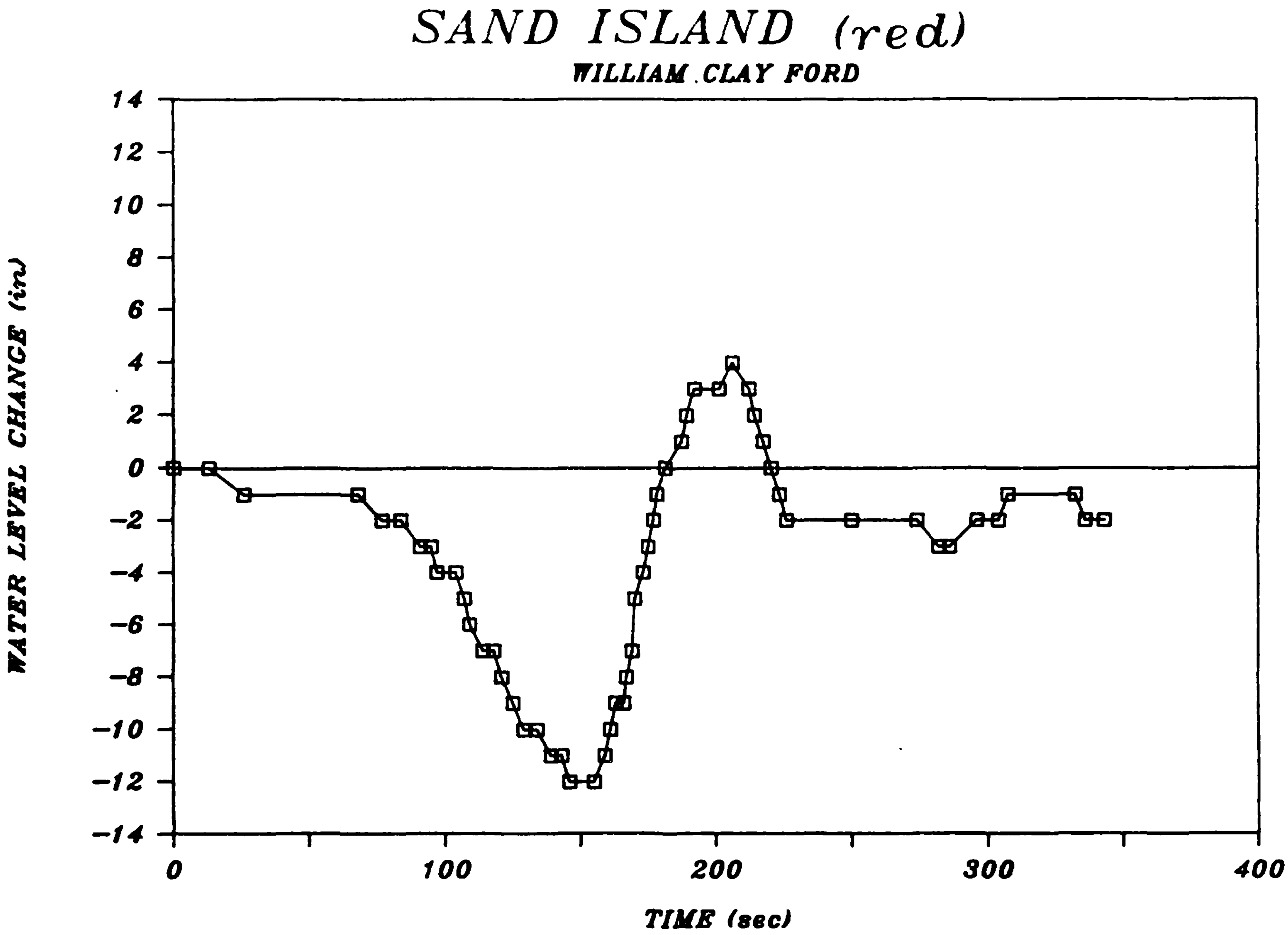

Figure 9. Water Level Change During a Vessel Passage

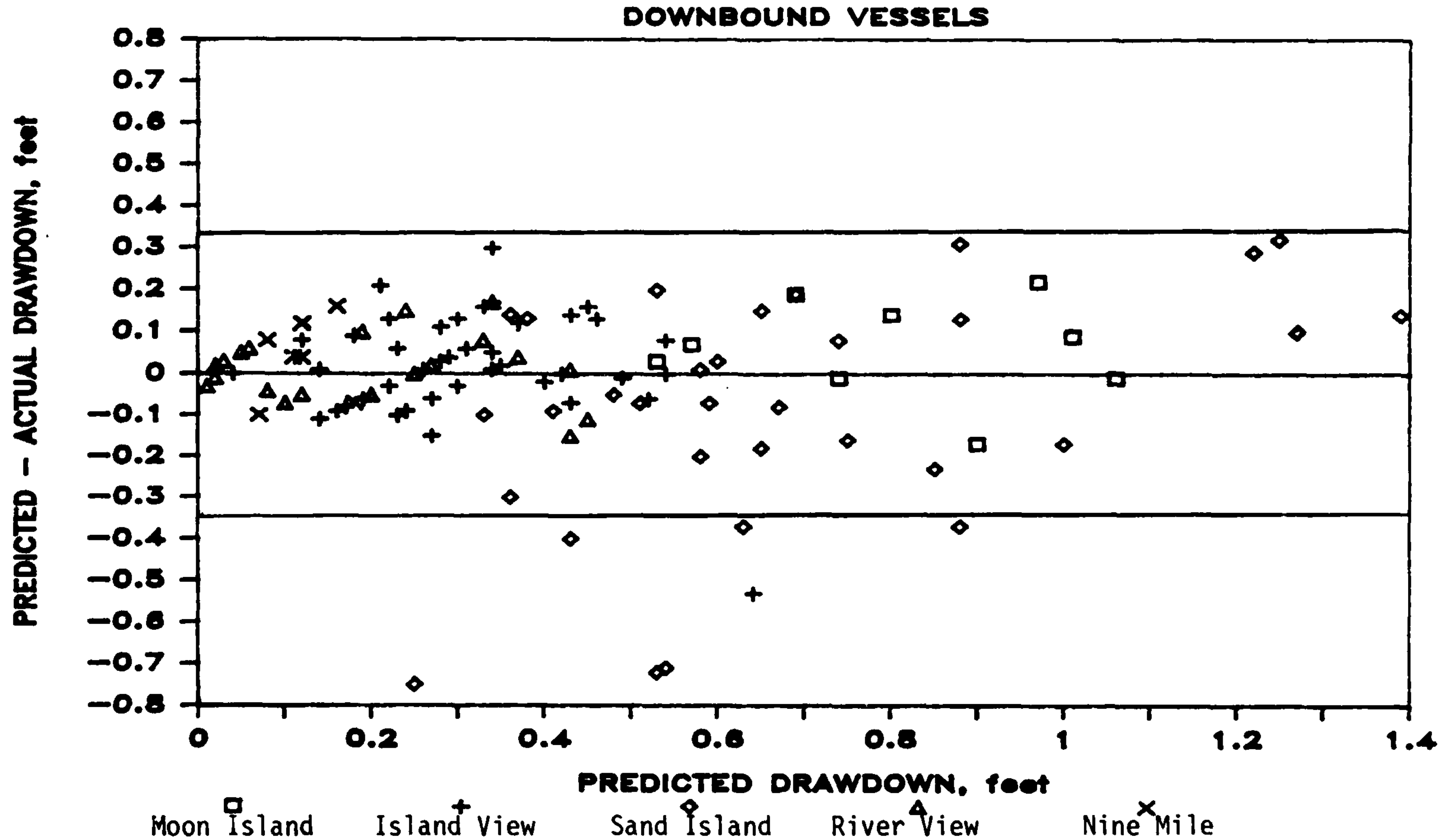

Figure 10. Quality of Drawdown Prediction for Downbound Vessels

also shown on Figure 10. This interval is between +0.334 and -0.350, the mean error is -0.008, and the median error is +0.010.

Figure 11 shows the comparison for upbound vessels. Using the same statistical treatment as was applied to Figure 10 (9) the 95% confidence level that errors will be within the bounded zone 90% of the time yields the bounds of +0.585 and -0.555. For these data the mean error is +0.015 and the median error is +0.010.

An inspection of Figure 9, the William Clay Ford downbound at Sand Island, shows a water level increase above ambient level immediately following the drawdown portion of the curve. This surge is common and seems to increase as the drawdown magnitude increases. To examine the effect and develop a relationship, surge to drawdown ratios were computed for the data sets in Appendix B. Figures 12 and 13 show the results for upbound and downbound vessels, respectively. The importance of a surge prediction is to evaluate whether an onshore bluff will be attacked, or whether flooding of nearby dwellings will occur during high water periods. Therefore it seems appropriate to develop a relation which would insure, with a high probability, that the surge would not exceed this value. The suggested relationship shown on both figures bounds a large majority of the observations. Its equation is indicated on the figures, and as a data base is developed, it can be modified accordingly.

It should be pointed out that the predicted vessel drawdowns were computed using the measured speed, observed draft, an approximate river velocity, a measured river cross-section, and an assumed vessel position in that cross-section. If a navigational range was available to the vessel it was assumed that the vessel was on that range. In the absence of a range it was assumed that the vessel was in the center of the channel. The sensitivity of

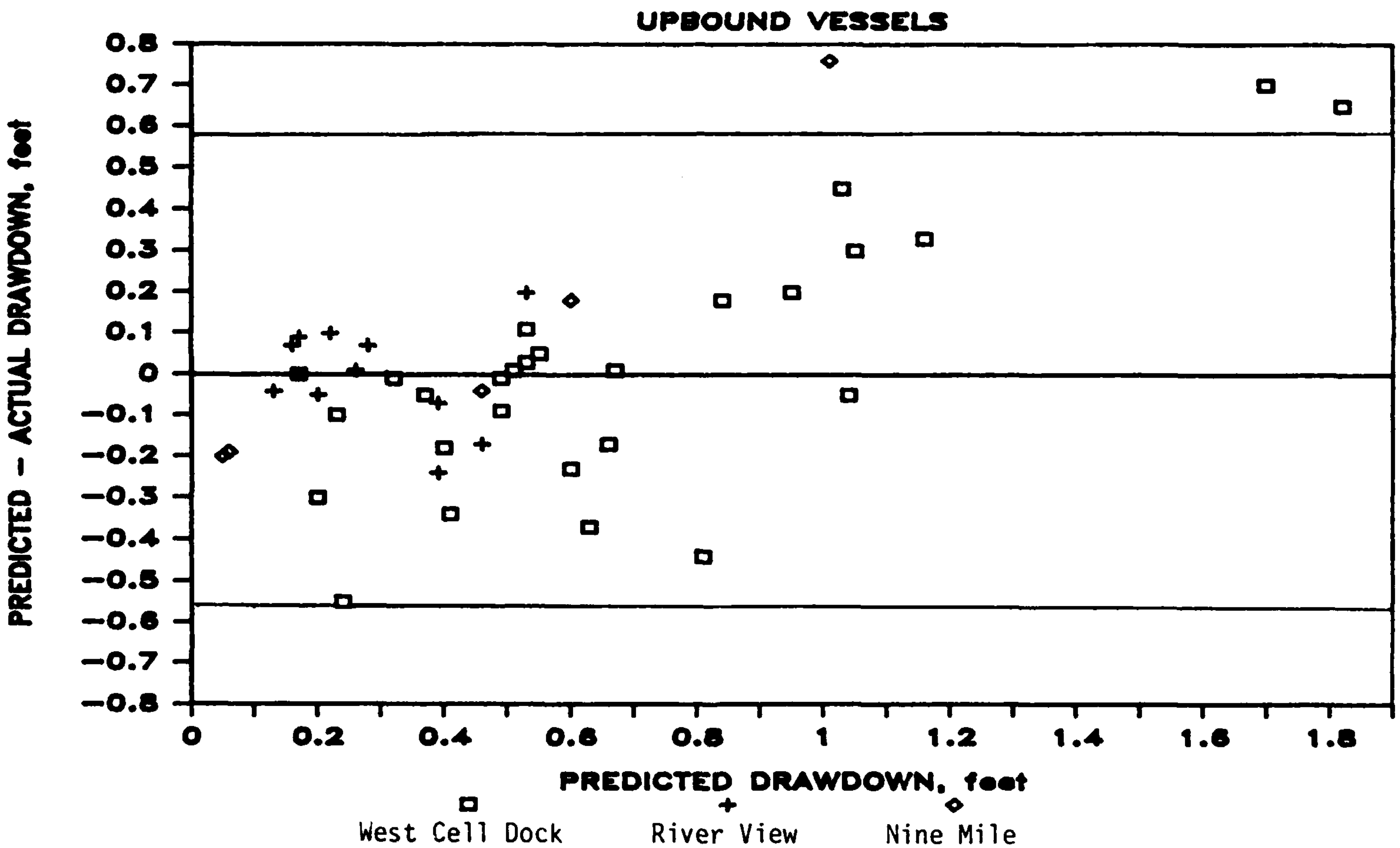

Figure 11. Quality of Drawdown Prediction for Upbound Vessels

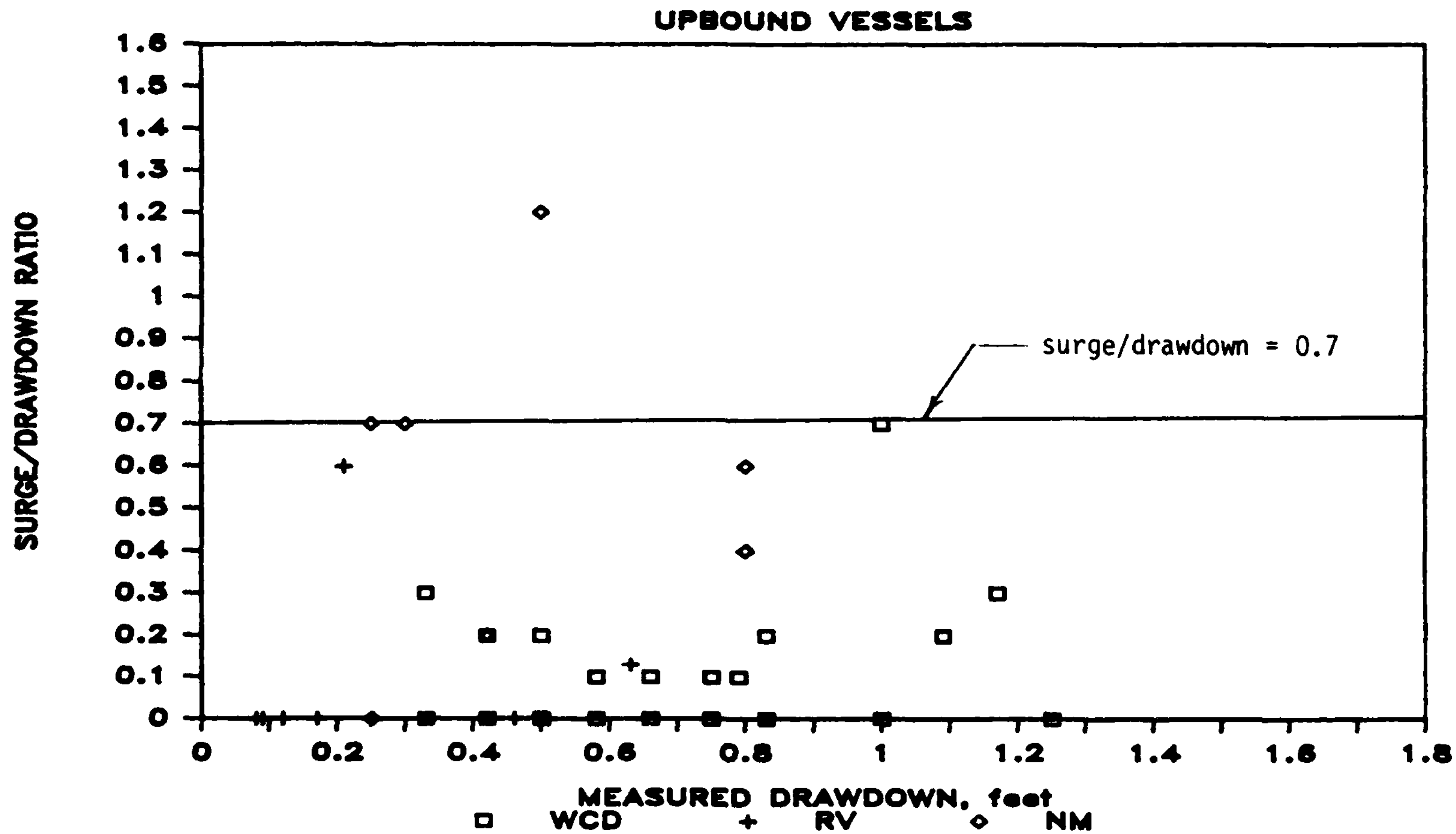

Figure 12. Observed Surge-Drawdown Relationship for Upbound Vessels

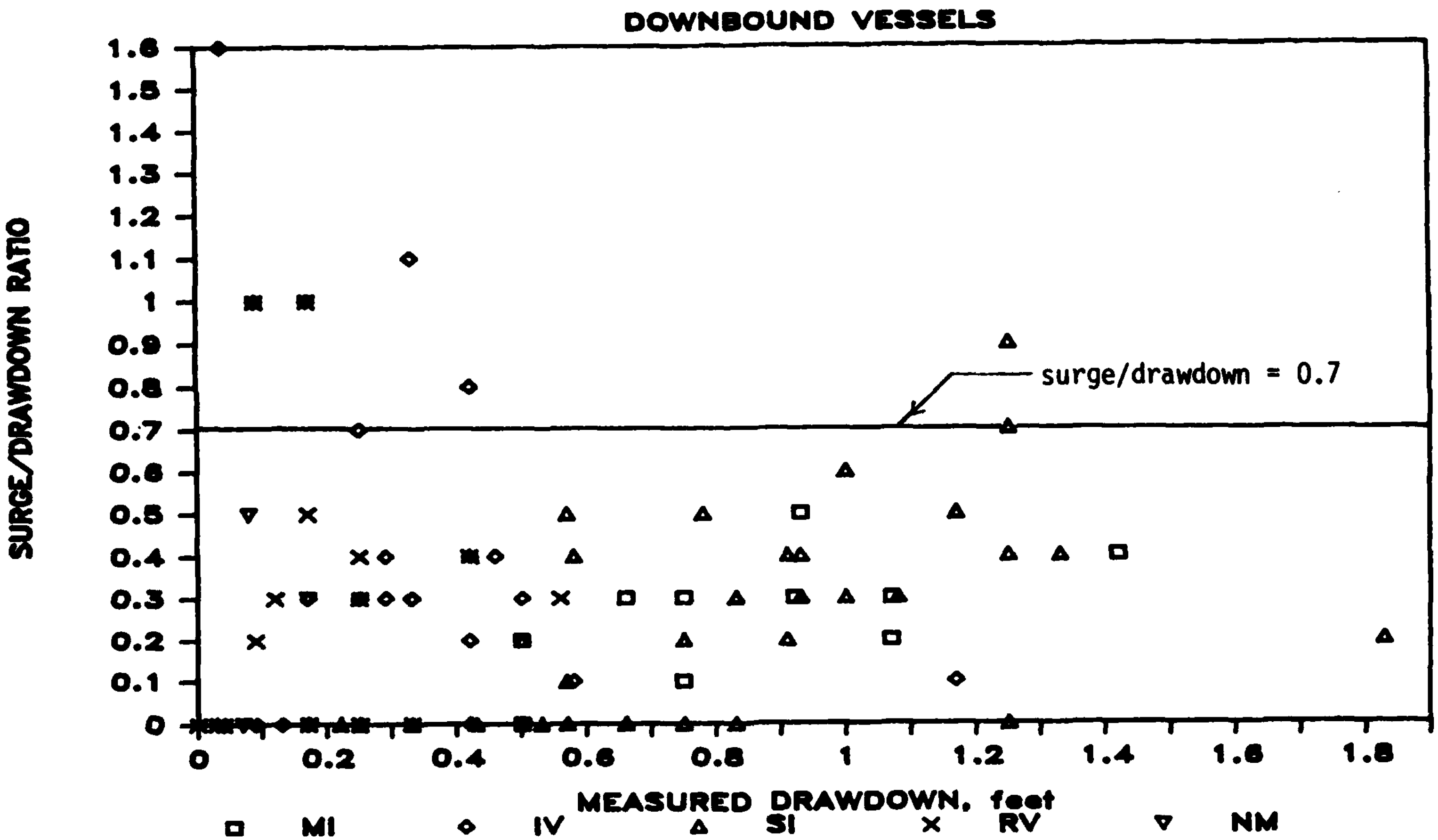

Figure 13. Observed Surge-Drawdown Relationship for Downbound Vessels

the predicted drawdown to some combinations of variables was not discovered until late in the observation program. Vessel position checks during the latter portion of the field program seemed to confirm the validity of the assumption, but one can speculate that the difference between measured and predicted drawdown may have been due in part to an incorrect positioning of the boat in the channel cross-section.

In summary, a surge/drawdown relation and a drawdown prediction model have been developed which are sufficiently accurate to assist in the assessment of variables and regulation schemes to assess damage related to vessel-induced drawdown.

SEDIMENT DISTURBANCE

A previous section of this report has shown the observed and computed relations concerning vessel-induced drawdown and surge water levels. This section deals with the observed as well as predicted disturbance to bottom sediments due to these water level fluctuations. The problem approach was twofold. One approach was to trap and measure the nearshore sediment if and when it moved in response to a vessel passage; the second approach was to measure sediment transport over a range of velocities in a laboratory flume, to make the appropriate theoretical corrections, and to compute sediment disturbance based on available nearshore measured vessel-induced velocity patterns.

Measured Sediment Disturbance

Just prior to the passage of a vessel an array of four steel sediment traps was placed on the river bottom in the nearshore zone. The array was arranged so that the trap directions were 90^0 apart so that they pointed downstream parallel to the channel (0^0 designation), shoreward perpendicular to the channel (90^0 designation), upstream parallel to the channel (180^0 designation), and riverward perpendicular to the channel (270^0 designation). During vessel passage water level-time data were collected, and an observer visually described the sediment disturbance as a function of the same time base as well. Immediately after the river flow pattern returned to ambient conditions following the vessel passage, each trap was retrieved and all material trapped was bottled and saved for later laboratory analysis.

Trap array locations were on the various site transects in two to three feet of water which located them from 10 to 40 feet offshore, depending on the site. The sediment traps themselves

had been developed in 1978 for this purpose. They were developed by means of flume studies utilizing sand-size material. Each trap is baffled, has a five-inch wide by four-inch high throat opening and is designed to collect any sediment moving within two inches of the river bottom.

Laboratory analysis of each trap sample consisted of a visual determination of the presence of organic material and/or aquatic animal life, drying and weighing of the mineral portion of the sample, and for selected samples sieving of the mineral portion to determine the soil's grain-size characteristics.

During this study 34 sediment trap data sets were collected during 22 vessel passages. Organic material was collected by at least one trap in the array for each passage and, depending on the location, animal life was occasionally trapped also. The vegetable matter was primarily partially decomposed non-woody fibrous material and algae, while the animal matter was caddisfly nymphs and fresh water snails. The grain-size distribution curves for the samples which were sieved are shown in Appendix A.

The dry weight of mineral soil collected by each trap is shown in Table 1. This table lists the site, vessel name (and direction of travel in a two-way channel), the measured drawdown in inches, the total sediment weight collected in the four-trap array, the net sediment weight collected and the direction of net sediment movement. The net sediment weight and direction of movement are computed by determining the magnitude and direction of the resultant of the weight vectors of the four traps in the array.

Table 1. Summary of Field Sediment Trap Results

	DRAWDOWN in.	SEDIMENT gm TOTAL	SEDIMENT gm NET	DIRECTION degrees		DEPTH ft
WEST CELL DOCK (green side)						
LEWIS WILSON FOY	7	37.24	20.03	275	TRAPS	
ELMGLEN	10	70.36	10.2	279	20 ft.	1.7
CANADIAN OLYMPIC	13	175.6	81.87	273	OFF -	
GEORGE A. STINSON	14	274.69	74.68	350	SHORE	
NANTICOKE	12	352.55	140.68	231		
PATTERSON	9.5	69.41	20.88	83	TRAPS	
COLUMBIA STAR	8	78.87	53.03	359	10 ft.	1.1
LEWIS WILSON FOY	7	144.03	12.88	73	OFF -	
GEORGE A. STINSON	9	183.8	105.97	280	SHORE	
NANTICOKE	12	122.56	26.89	29		
PATTERSON	9.5	49.47	11.41	283	TRAPS	
COLUMBIA STAR	8	152.09	11.6	81	30 ft.	2.4
LEWIS WILSON FOY	7	65.67	34.57	282	OFF -	
GEORGE A. STINSEN	9	308.28	125.61	349	SHORE	
SAND ISLAND (red side)						
W. A. McCONAGLE	7	12.36	2.58	215		
H. LEE WHITE	6	2.77	0.28	180		
WILLIAM CLAY FORD	9.5	26.59	5.74	317	TRAPS	2.5
STEWART J. CORT	11	12.41	3.18	228	30 ft.	
FRONTENAC	6	5.27	1.7	268	OFF -	
CHARLES M. BEEGHLY	9	37	20.84	304	SHORE	
JAMES R. BARKER	11	36.26	9.35	211		
SAND ISLAND (green side)						
W. A. McCONAGLE	4	0.75	0.42	184		
H. LEE WHITE	3	2.37	0.74	67		
WILLIAM CLAY FORD	5	2.01	1.11	192	TRAPS	2.5
STEWART J. CORT	7	7.4	1.6	248	40 ft.	
FRONTENAC	2.5	3.23	2.56	358	OFF -	
CHARLES M. BEEGHLY	6.5	10.01	0.62	143	SHORE	
JAMES R. BARKER	7	10.75	5.27	278		
RIVER VIEW (green side)						
ALGOWEST (up)	2	3.05	2.21	299		
J. N. McWATTERS (down)	3	0.17	0.17	107	TRAPS	
BENSON FORD (down)	3	0.67	0.21	0	15 ft.	2.0
CHARLES E. WILSON (up)	3	0.35	0.28	358	OFF -	
STEWART J. CORT (up)	3	2.74	2.35	351	SHORE	
MIDDLETOWN (down)	1	0.1	0.08	45		

Computed Sediment Disturbance

During previous observation between 1977 and 1980 two of the authors occasionally observed a bottom instability termed "explosive liquifaction" which would occur when the passing vessel induced a particularly large water level drawdown. Also during this previous study period several sets of water velocity-direction-time data were collected during vessel passages. Therefore, it was decided to perform a flume study in the laboratory to better understand the explosive liquifaction phenomenon and to develop a sediment transport-water velocity relationship for sand similar to that at the sites where velocity-direction-duration data sets are available. This would allow the sediment disturbance to be predicted although it was not directly measured.

The portion of the laboratory study devoted to the explosive liquifaction did not provide an explanation of the observed field phenomenon as it apparently did not adequately model the necessary field conditions. Due to the infrequency of this occurring in the field under usual vessel operations, this portion of the study was discontinued.

Tests were continued, however, to establish the velocity-transport relationship. A good relationship was developed for subrounded quartz sand with maximum and minimum grain sizes of 0.420 mm (#40 sieve) and 0.250 mm (#60 sieve), respectively. The maximum average flow velocity in the flume was limited to 1.6 fps due to an inability to accurately measure the sediment transport rate at higher velocities.

This transport relation was then described mathematically by performing a linear regression analysis to determine a second-order curve for a log-log coordinate system. The resulting equation has the form:

$$\log (g_s) = A (\log V)^2 + B (\log V) + C$$

where g_s = sediment transport rate
V = average flow velocity in the flume
A, B, C = constants.

To relate flume velocity to those measured in the field, the vertical velocity distribution in a turbulent flow field was used. According to Yalin (17) it is:

$$\frac{V}{V^*} = 2.5 \ln \frac{d}{k_s} + 8.5$$

where V = velocity at depth d
V_* = shear velocity
d = distance of velocity measurement above bed
k_s = roughness coefficient = 2.0 x average soil particle diameter.

By equating the shear velocity in the field to that in the flume one obtains:

$$\frac{V_{flume}}{2.5 \ln \frac{d_{flume}}{k_s} + 8.5} = \frac{V_{field}}{2.5 \ln \frac{d_{field}}{k_s} + 8.5}$$

The d_{flume} did not vary significantly, and a value of 0.4 x total depth was used for d_{flume}. Due to the nature of the equipment used, the depth at which the field velocity was measured varied with the field velocity. By geometry and a calibration curve the field measurement distance above the bed was determined to be:

$$d_{field} = \sqrt{(10.25)^2 + [\log^{-1} (\frac{V-b}{m})]^2}$$

where

V = field velocity

b, m = constants.

By substitution into the previous equation the relation between flume and measured field velocities is developed.

This now allows a sediment transport rate to be predicted for a measured field velocity. If a simple vector equation describing velocity change with time can be determined, the given sediment transport relation could be vectorally integrated over time to yield a net quantity of sediment transported. However, the observed velocity patterns are too complex for this approach, and a computer algorithm was developed to perform the integration.

The computer program developed performs an integration of the vector quantity g_s (weight/time) as a function of time over the period of the drawdown. The field data are entered at various points giving time, velocity and direction to describe the drawdown period. The program then performs iterations over every one-second period linearly interpolating both velocity and direction between each point. The quantity of sediment is determined and directional component magnitudes are calculated. The components are parallel to shore and perpendicular to shore. These component magnitudes are calculated at every iteration and stored in an array for later summing. After the last iteration is performed the components are summed and a resulting magnitude and direction are calculated.

Published relationships between sediment transport and river velocity are also available. The Colby relationships (4) have been developed based on a compilation of many flume studies. This

published information was also used to predict net transport and direction as previously described.

Table 2 summarizes the sediment transport due to some particular vessel passage based upon its recorded nearshore water velocity pattern. The River View and Nine Mile sites approximate those described in this present report, while the Adams and Gleason sites on the St. Marys River and the Russell Island and Chrysler sites on the St. Clair River were used in previous studies.

The results are expressed as sediment disturbance, which is the scalar integration of sediment movement, and as net transport, which is the vector integration of sediment movement.

The net sediment transport direction uses the sign convention established previously for the field sediment disturbance data; that is, 0^{o} is downstream, 90^{o} is shoreward perpendicular to the channel, 180^{o} is upstream, and 270^{o} is channelward perpendicular to the channel. Since the sediment transport is movement past a location, the unit selected was pounds of sediment passing through a vertical window one foot wide in the direction perpendicular to the direction of net transport per vessel passage, or simply lb/ft. The comments also indicate whether the velocity pattern was obtained when an ice cover was present or absent.

Analysis of Sediment Disturbance Results

Depending on the water velocity induced by a particular vessel, a considerable amount of sediment may be moved without resulting in net sediment transport occurrence, yet this movement could be environmentally damaging. In the event that net movement

Table 2. Summary of Laboratory Predicted Sediment Movement

VESSEL		DRAWDOWN (in.)	LAB PREDICTION DISTURBANCE lb/ft	LAB PREDICTION TRANSPORT NET lb/ft		DIRECTION degrees	COLBY RELATIONS SEDIMENT TRANSPORT lb/ft NET	DIRECTION degrees
RIVER VIEW								
ROGER BLOUGH MARCH 14, 79	DOWN	7	2.62	2.51	ICE	90	0.786	86
IMPERIAL ST. CLAIR MARCH 14, 79	UP	4	10.67	10.65	ICE	8	4.72	8
STEWART J. CORT APRIL 19, 79	UP	6	14.36	14.3	OPEN	9	3.43	10
JOHN G. MUNSON APRIL 19, 79	UP	2.5	0.37	0.36	OPEN	36	0.21	35
PHILLIP D. BLOCK APRIL 19, 79	DOWN	7	0.03	0.028	OPEN	17	0.019	13
NINE MILE								
PHILLIP R. CLARKE JAN 18, 79	DOWN	8.4	0.66	0.66	ICE	186	0.42	185
J. BURTON AYERS OCT 15, 77	UP	10	4.84	4.34	OPEN	324	1.68	331
SIR JAMES DUNN AUG 31, 78	UP	7.7	3.12	0.092	OPEN	217	0.1	237
COLLINGWOOD OCT 15, 77	UP	5	0.01	0.008	OPEN	0	0.007	1
BLACK BAY OCT 7, 77	UP	3	0	0	OPEN		0.005	111
TADOUSSAC OCT 15, 77	DOWN	4	0	0	OPEN		0	
ANDERSON AUG 31, 77	UP	12.6	5.49	0.75	OPEN	78	0.57	80
ADAMS								
EDWARD L. RYERSON JAN 21, 78	DOWN	7	0.6	0.6	ICE	359	0.36	359
HOYT JAN 21, 78	UP	6.5	8.1	8.1	ICE	0	1.5	0
GLEASON								
PHILLIP R. CLARKE FEB 16, 79	UP	14.8	66.3	51.2	ICE	320	12.83	327
CASON J. CALLOWAY FEB 16, 79	UP	14.8	62.7	59.6	ICE	300	16.6	300
RUSSELL ISLAND								
LAKE WINNIPEG APRIL 15, 78	UP	9	5.5	5.5	OPEN	0	1.79	0
RAVNI KOTARI JUNE 22, 78	DOWN	6.7	0.24	0.02	OPEN	23	0.01	22
CHRYSLER								
EDWARD GREEN JUNE 23, 78	DOWN	8.7	0.06	0.045	OPEN	210	0.024	210

does occur, both the net magnitude and the direction of travel are important.

Figure 14 is a plot of all 34 of the 1985 sediment trap data sets showing weight of sediment trapped (the arithmetic sum for a four trap array for one vessel passage) as a function of the measured vessel-induced drawdown. It shows that downbound vessels caused much less sediment disturbance than upbound vessels at comparable drawdowns. It also shows that upbound vessels which create a drawdown of six inches or less cause a relatively minimal disturbance.

The considerable data scatter is not unexpected since the developed velocity patterns may be highly influenced by local bathymetry and shoreline shape. However, for drawdowns greater than six inches the data do suggest an exponential relation between vessel-created drawdown and the resulting weight of sediment disturbed per unit of bottom area.

The predicted sediment disturbances based on the laboratory study and available velocity patterns as a function of observed drawdown are shown in Figure 15. This figure shows the same general relations as the previous figure. That is, downbound vessels caused much less disturbance than did upbound vessels at the same drawdown, and that one could generalize and say that minimal disturbance is induced at drawdowns of less than six inches. It is interesting to note, however, that the upbound data point which does predict measurable disturbance is at River View with an ice cover. Due to the relative lack of data and the indirect method used to develop them, this figure is less conclusive than Figure 14.

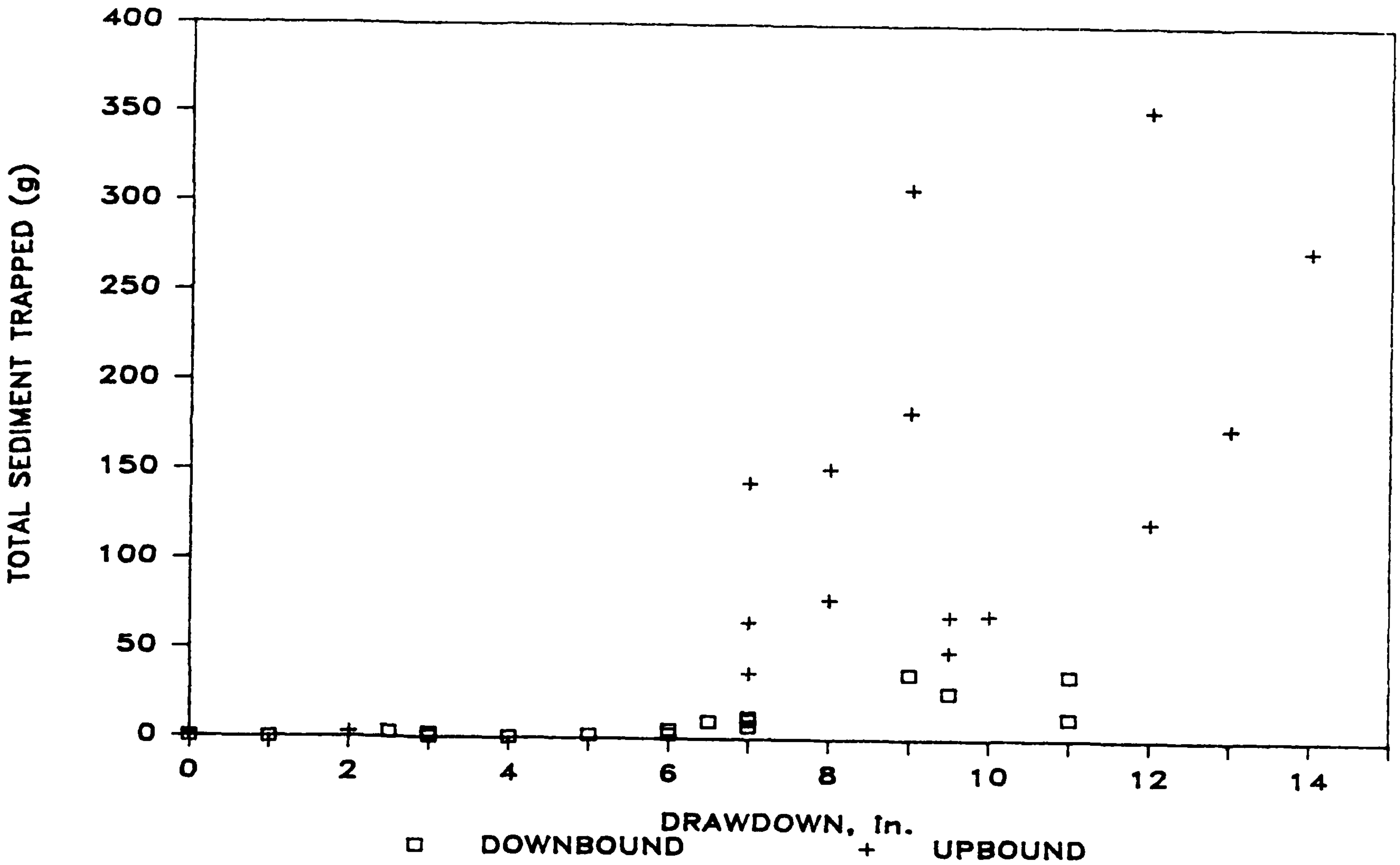

Figure 14. Sediment Disturbance in Relation to Measured Drawdown

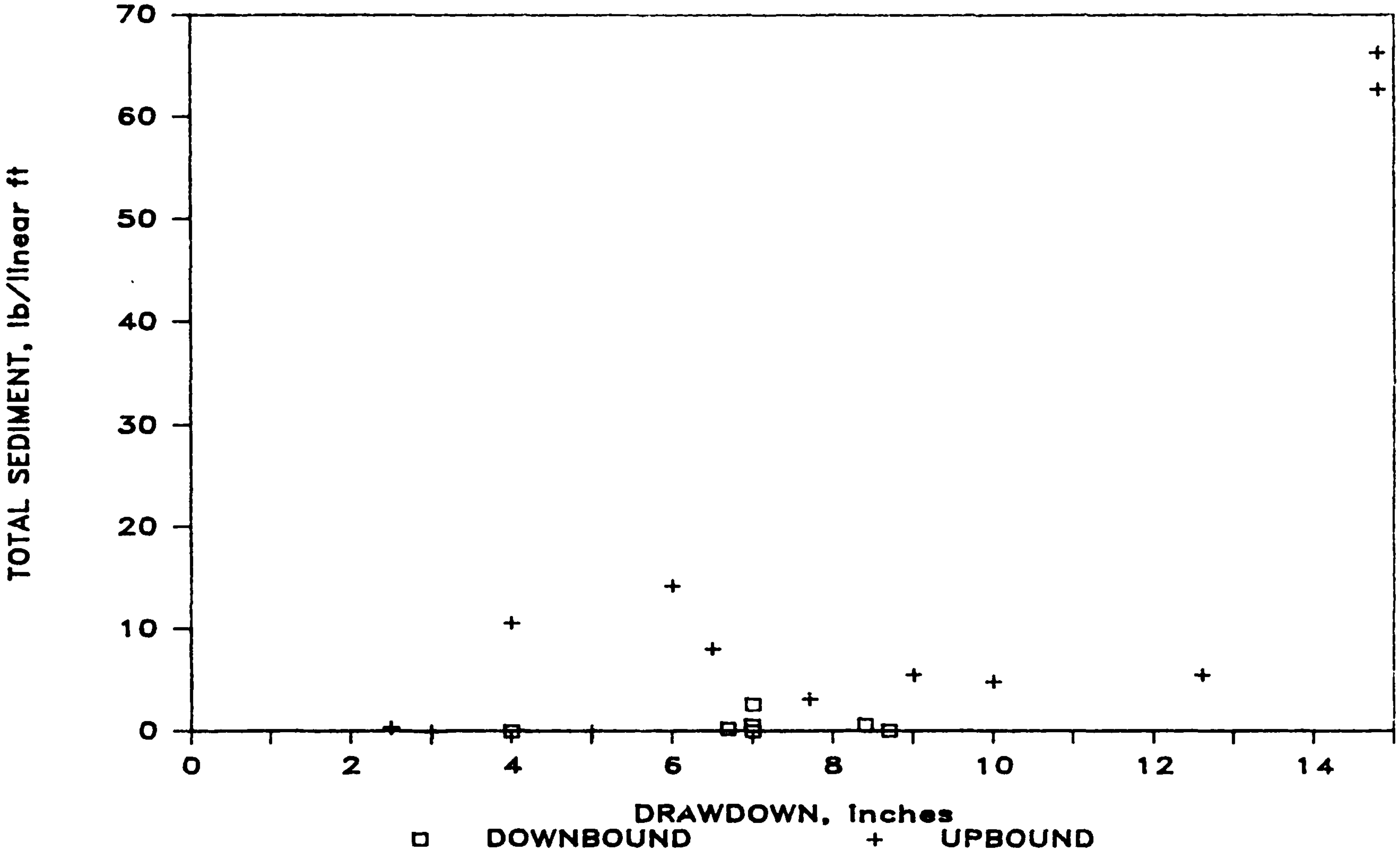

Figure 15. Predicted Sediment Disturbance in Relation to Measured Drawdown

Figures 16 and 17 show the direction of net sediment transport as a function of vessel-induced drawdown in upbound and downbound channels, respectively. The angle convention shown on the figures does not obscure any data points. Figure 16 shows the net sediment transport direction to be offshore for 10 out of 14 or 71% of the data sets from nine vessel passages in the upbound direction. Figure 17 shows this same trend for downbound vessels where 12 out 14 or 86% of the data sets representing seven vessel passages indicate net offshore sediment movement.

Figure 18 presents the direction of sediment movement utilizing the lab work and field velocity patterns. As might be expected, the relation is less clear, but discounting drawdowns of six inches or less and those which only show movement parallel to the channel, 6 out of 10 or 60% of the data indicate net offshore movement.

Impacts and Mitigation

The impacts of a high degree of sediment disturbance without significant net transport would be speculative on the part of the writers and hence will not be discussed. However, certain general observations can be made. Higher level benthic organisms can be temporarily suspended and moved laterally, and in general a transient turbidity occurs in the nearshore zone as organics and the fine soil fraction are temporarily suspended.

The impacts of net offshore sediment movement are much better understood and amenable to analysis on a case by case basis. Sediment moving offshore in the nearshore zone will either decrease the channelward bottom slope, be deposited in the channel, or a combination of both. This results in a higher level of maintenance dredging than would be anticipated from sediment transport

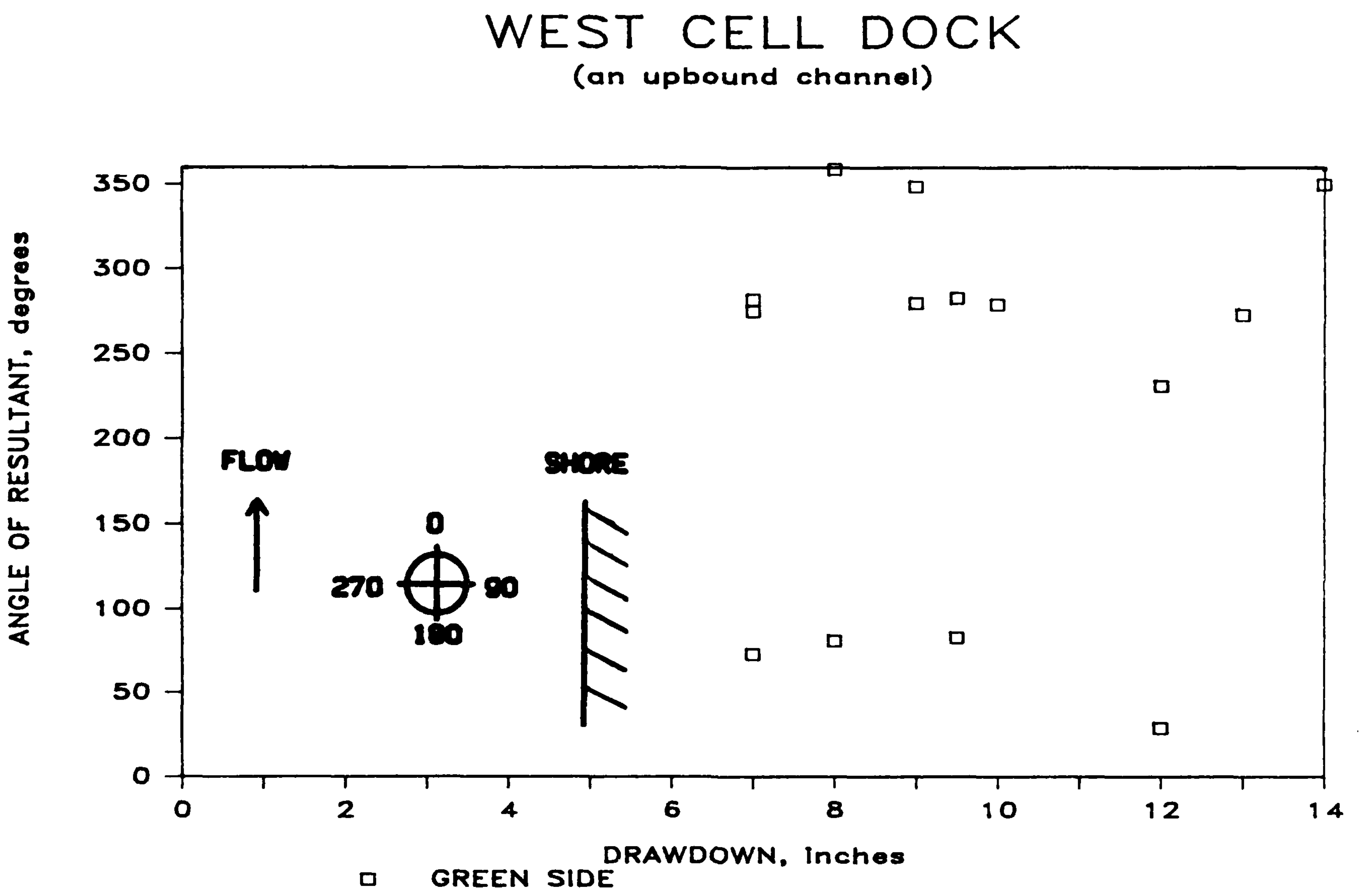

Figure 16. Resultant Direction of Sediment Movement from Trap Data in Relation to Measured Drawdown, Upbound Vessels

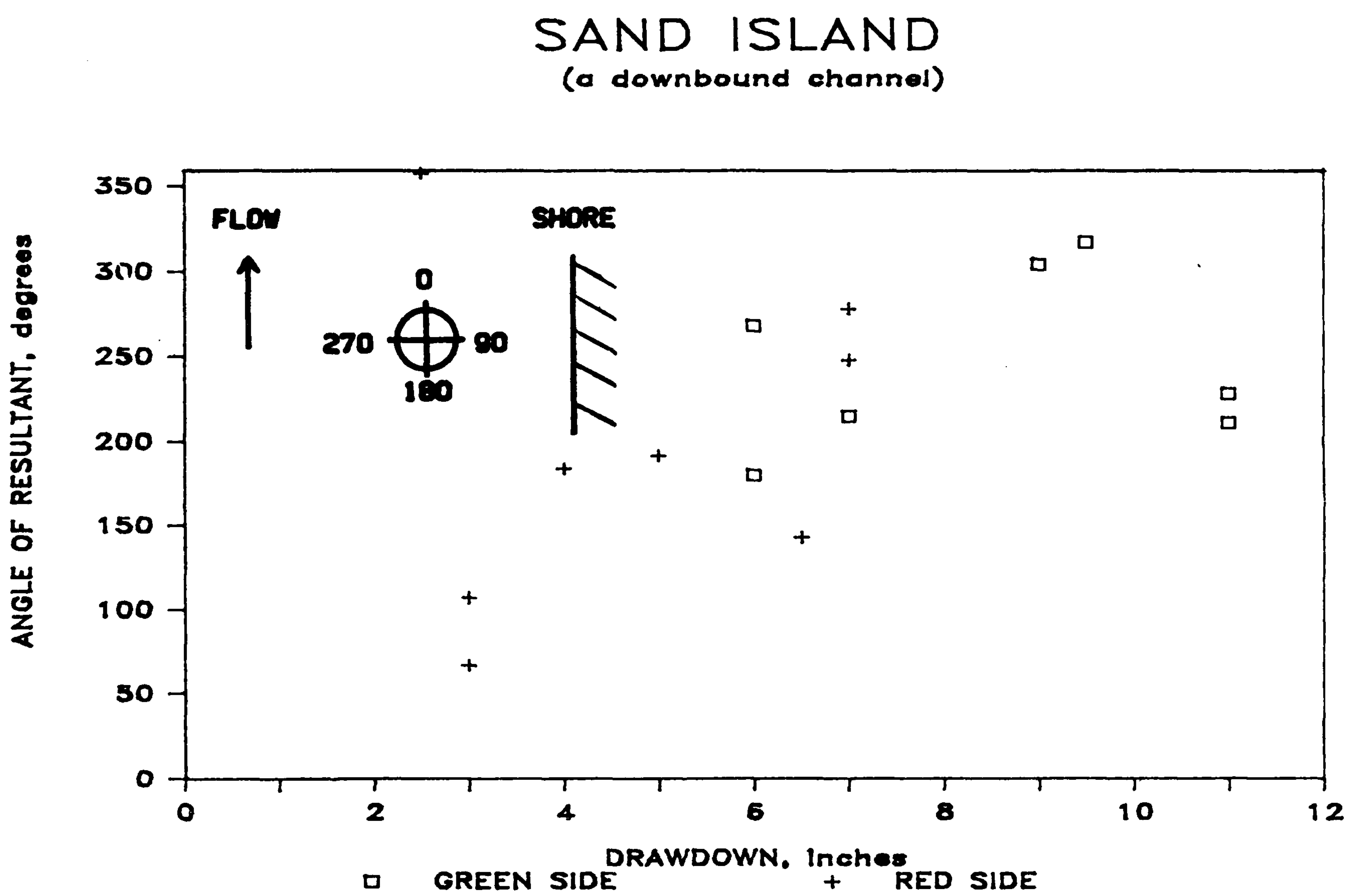

Figure 17. Resultant Direction of Sediment Movement from Trap Data in Relation to Measured Drawdown, Downbound Vessels

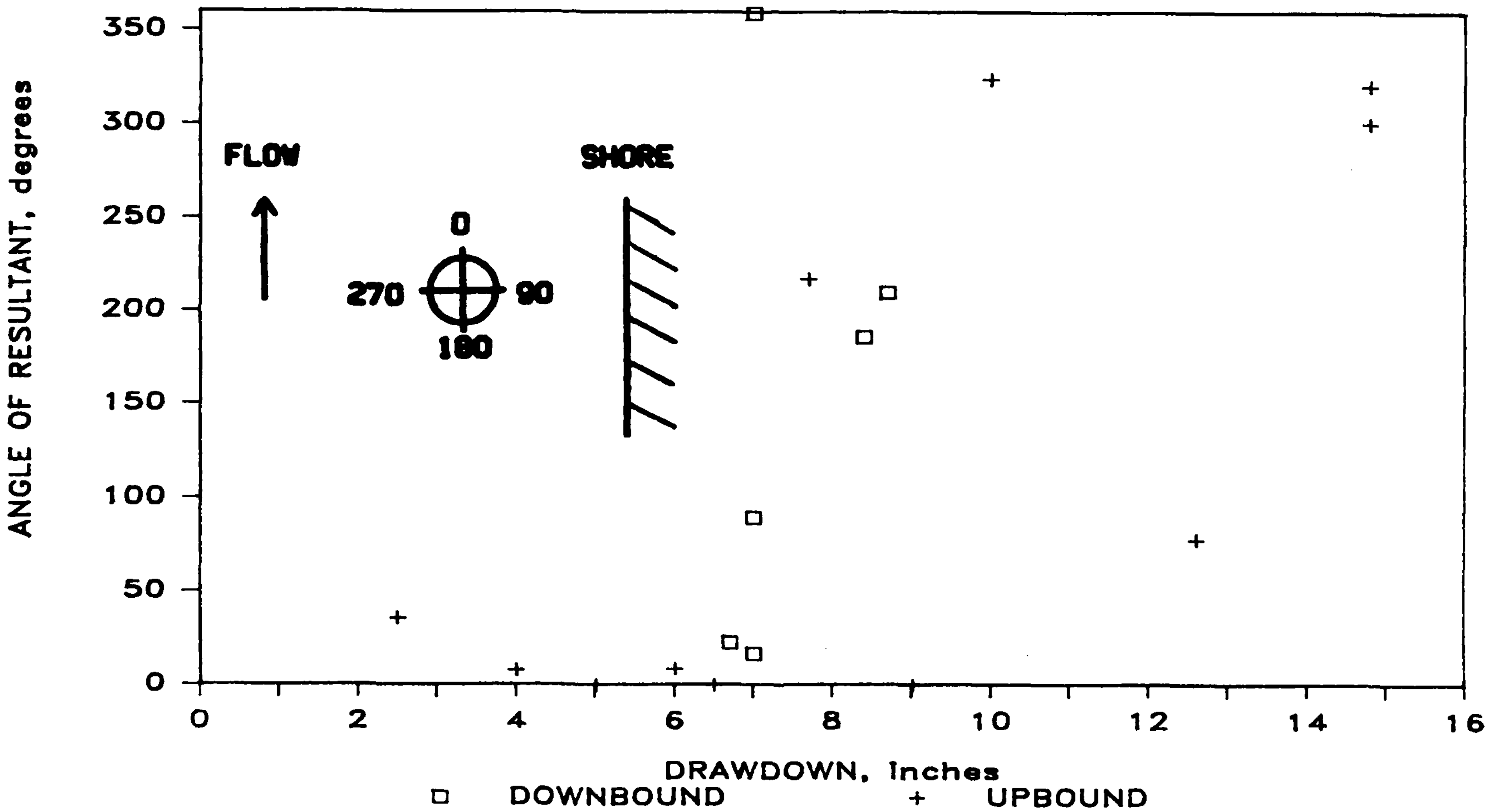

Figure 18. Lab Predicted Direction of Sediment Movement in Relation to Measured Drawdown

into the system by streams from the uplands. The sources of the sediment being transported channelward are three. It may come from a deepening of the nearshore zone, it may be available from bank recession, or it may come from some updrift source in which case at the site in question no erosion would be evident. However in the absence of an updrift source, net sediment transport channelward results in bank recession, nearshore deepening, or a combination of the two.

Based on the data presented in this study, limiting vessels to speeds which would cause no more than six inches of drawdown in restricted channelways would reduce these impacts.

MODEL PREDICTION OF RELATIVE DAMAGE

The predictive model contains an option which allows the user to assess the potential for shore and nearshore damage as: none to light, moderate, or high. This assessment is based on sediment movement due to vessel-induced water velocity and surge. It does not assess the potential for damage due to ice forces on structures.

"None to light" damage is defined as a nearshore bottom condition where the induced water velocity pattern is such that only organic matter resting on, but not rooted in, the bed will move. Mineral sediment movement is inconsequential.

"Moderate damage" is defined as a nearshore bottom condition where the induced velocity pattern is such that organic matter resting on the bottom moves, and individual mineral particles move along the bed as bedload. It is implied that the net direction of mineral particle movement is offshore. Many repetitions of this cycle will lead to identifiable deepening of the nearshore zone and/or bank recession.

"Severe damage" is defined as a nearshore bottom condition where the induced velocity pattern is such that shallow-rooted organics are displaced, and mineral sediment is suspended and thereby transported some considerable distance in the offshore direction. The surge which typically follows the water level drawdown is of sufficient magnitude to wash sediment shoreward from the backbeach or impinge on a bluff above the beach. Only a few repetitions of this cycle are necessary to produce deepening of the nearshore zone and/or beach recession and/or bank slumping and recession. This deepening of the nearshore zone could be only temporary, depending on other littoral processes acting in the environment.

The transitions from one class of damage to another are based on visual observations in the field combined with the guidance of the Fortier-Scobey relations for sediment transport (10). The damage transitions incorporated into the model, in terms of predicted drawdown, are as follows:

Damage Classes Associated with Bed

	Drawdown		
Bed	0 to 6"	6" to 12"	above 12"
Boulders and or cobbles	none to light	none to light	none to light
Coarse to medium sand	none to light	moderate	severe
Medium sand to silt	none to light	moderate	severe
Clay	none to light	none to light	none to light

Neither a boulder/cobble bed nor an intact clay bed will suffer noticeable disturbance in the range of drawdowns imposed by observed vessel passages, while the more commonly occurring nearshore sands and silts can experience significant movement in the presence of typical drawdowns.

Damage predictions supplied as output from the computer prediction (none to light, moderate, or severe) relate directly to that portion of the nearshore zone where the water depth is four feet or less and shorefast ice is not resting on the bed.

The shoreward area above the natural water level may include a beach face, a backshore with or without a beach scarp, and a bluff or escarpment; or the water surface may terminate in some configuration of manmade shore protection. All of these features are present at one point or another along the St. Marys River and the natural configurations involve a wide range of soils, from cobbles to highly plastic clays. The damage caused by vessel-

induced surge depends on the backshore topography and soil type. In turn, the backshore zone which will be attacked at some particular surge height depends on the natural water level. Therefore, the impact assessment must be done on a very local, or site specific, basis and must include an estimate of the surge height and shore ice characteristics.

The offshore extent of the zone of grounded shore ice cannot be predicted at this time. However, repeated vessel-induced surges during subfreezing temperature periods will provide an ice coating on the backshore zone or bluff which may be wetted prior to the development of grounded shore ice. Either of these barriers will effectively mitigate further damage above the normal shoreline during extended season navigation.

The predicted surge height used in this report is derived from Figures 12 and 13 which report surge/drawdown ratios observed during this study. The suggested relationship is shown in Figure 19.

Ice cover often protects the shore from erosional damage due to vessel-induced surges. As reported earlier, shorefast ice commonly develops prior to the end of normal navigation. As this ice thickens an ice crack develops several feet offshore and parallel to the shore due to a flexural failure of the sheet caused by the water level drawdown and surge associated with normal vessel traffic. This crack will typically remain open and the ice shoreward of it will thicken by downward growth and snow ice accumulation and eventually rest on the bed. Once this condition develops, the entire bed shoreward of the crack and the entire backshore are effectively insulated from any further vessel-related damage until the shorefast ice melts and/or floats away in the spring.

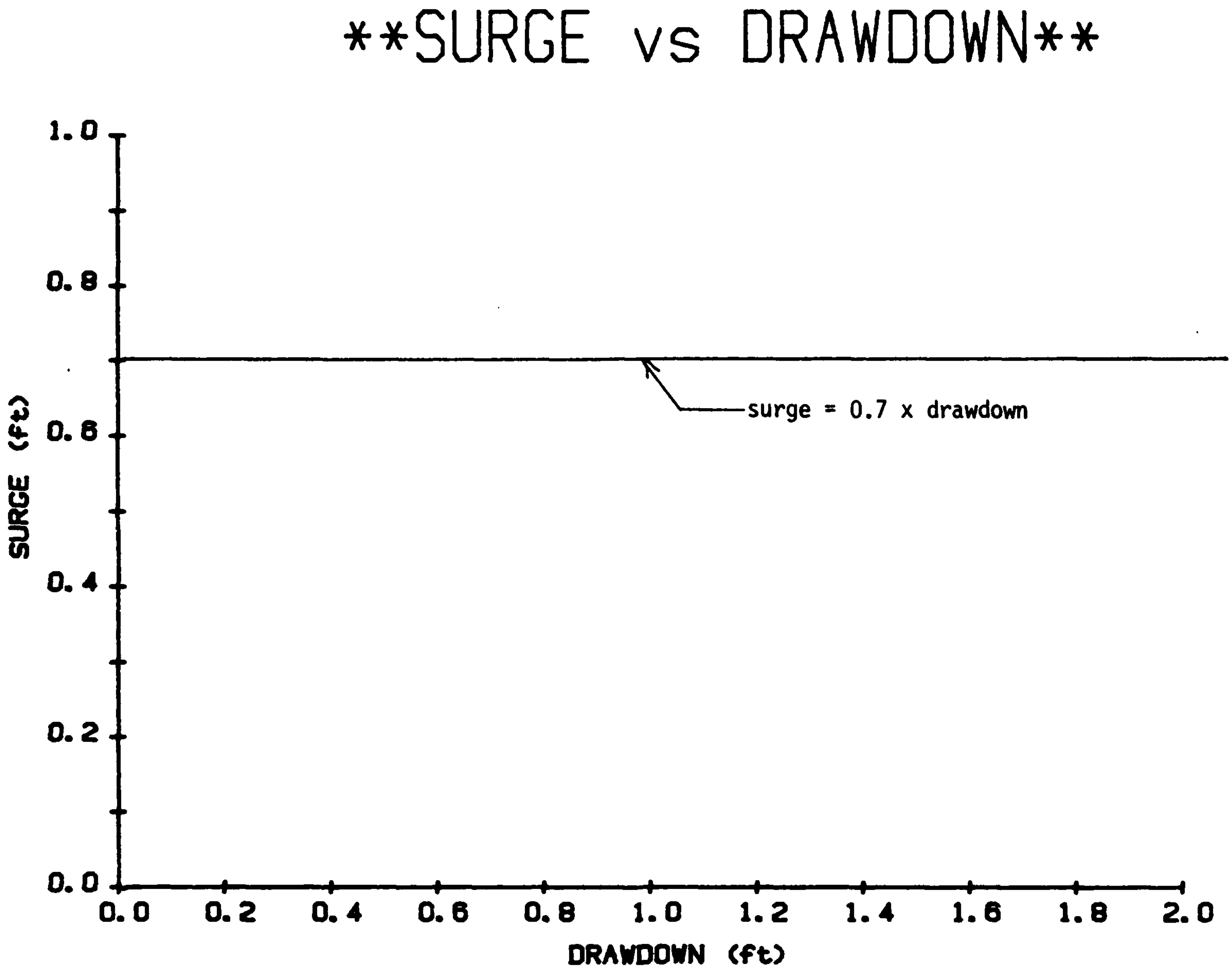

Figure 19. Recommended Relationship Between Surge and Drawdown

A more complex crack pattern usually develops where pile supported or crib structures are located riverward of the grounded shorefast ice. The effects of the ice cover on these structures are addressed later in this report.

RIVER TURBIDITY AND LIGHT EXTINCTION CHARACTERISTICS

During the winter navigation demonstration program, observed vessel-induced turbidity was minimal and temporary. It was not measured directly in a quantitative sense; rather, the procedure used for induced current measurements required visual observations of a tethered float. The float was never obscured for more than a few seconds, and after the sand to silt-size sediment had settled from suspension no increase in background level turbidity was apparent. In the presence of a continuous ice cover Alger (1) did note an increase in turbidity at the Gleason site after the third of a series of upbound vessels had passed on February 16, 1979, but also remarked that no change in turbidity was observed at the River View site when vessels passed.

During this present study, which was limited to vessel passages under ice-free conditions, changes in turbidity were often noticed. The nearshore zone at Nine-Mile red side, River View red side, and both sides at Moon Island were often sufficiently turbid that no visual bottom observations were possible and even sediment traps would be invisible in only a six-inch water depth. It has been observed that the common source of the turbidity is a clay bluff which is being subjected to frequent water level changes. In the absence of wind-driven waves, nearshore turbidity develops with the passage of each vessel. In the presence of natural waves of about six inches amplitude or more for any significant period of time, a high level of turbidity may extend from the shore to the navigation channel itself. During the course of this study the superposition of vessel-induced turbidity was not observed.

As a part of this study light extinction profiles were developed, and turbidity measurements were made at a number of locations at various times. These results are discussed separately below.

Light Extinction Profiles

Light absorption characteristics in the 0.4 to 0.7 micron wavelength range were determined at the various sites by making light versus depth profiles with a Li-Cor spherical quantum sensor measuring photon flux density in microeinsteins $s^{-1}m^{-2}$, where one microeinstein equals 6.02×10^{17} photons. The profiling results are given in Appendix C--Observed Ice Thicknesses and Water Turbidities--as raw data of light reading versus depth and as nondimensional plots with the light extinction coefficient noted on each plot. Each light extinction coefficient represents the slope from linear regression analysis.

The light extinction coefficient, K_e, is defined as follows:

$$I = I_o e^{-K_e Z} \text{ (Lambert's Law)}$$

where I = the light intensity at depth Z

I_o = the light intensity at zero depth

e = 2.718

and rearranging: $$K_e = \frac{-\ln (I/I_o)}{Z}$$

Thus, K_e is the slope of the curve. As K_e increases, the light transmission decreases. A typical profile is shown in Figure 20, and its normalized plot from Appendix C is shown in Figure 21. This data set was taken at the center of the channel just <u>after</u> the closely spaced passages of the 730 foot Saskatchewan Pioneer

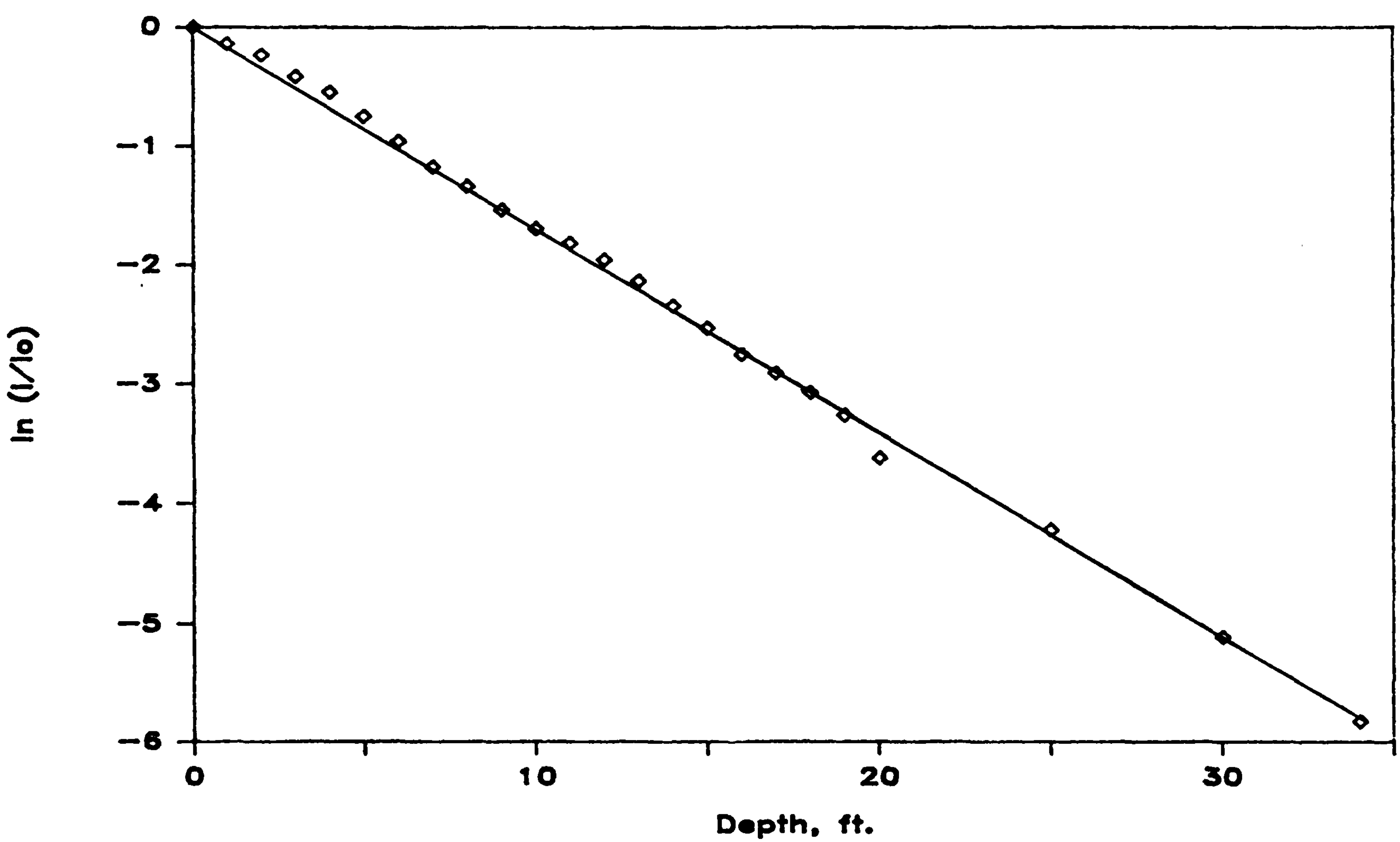

Figure 20. Light Extinction Profile After Vessel Passages

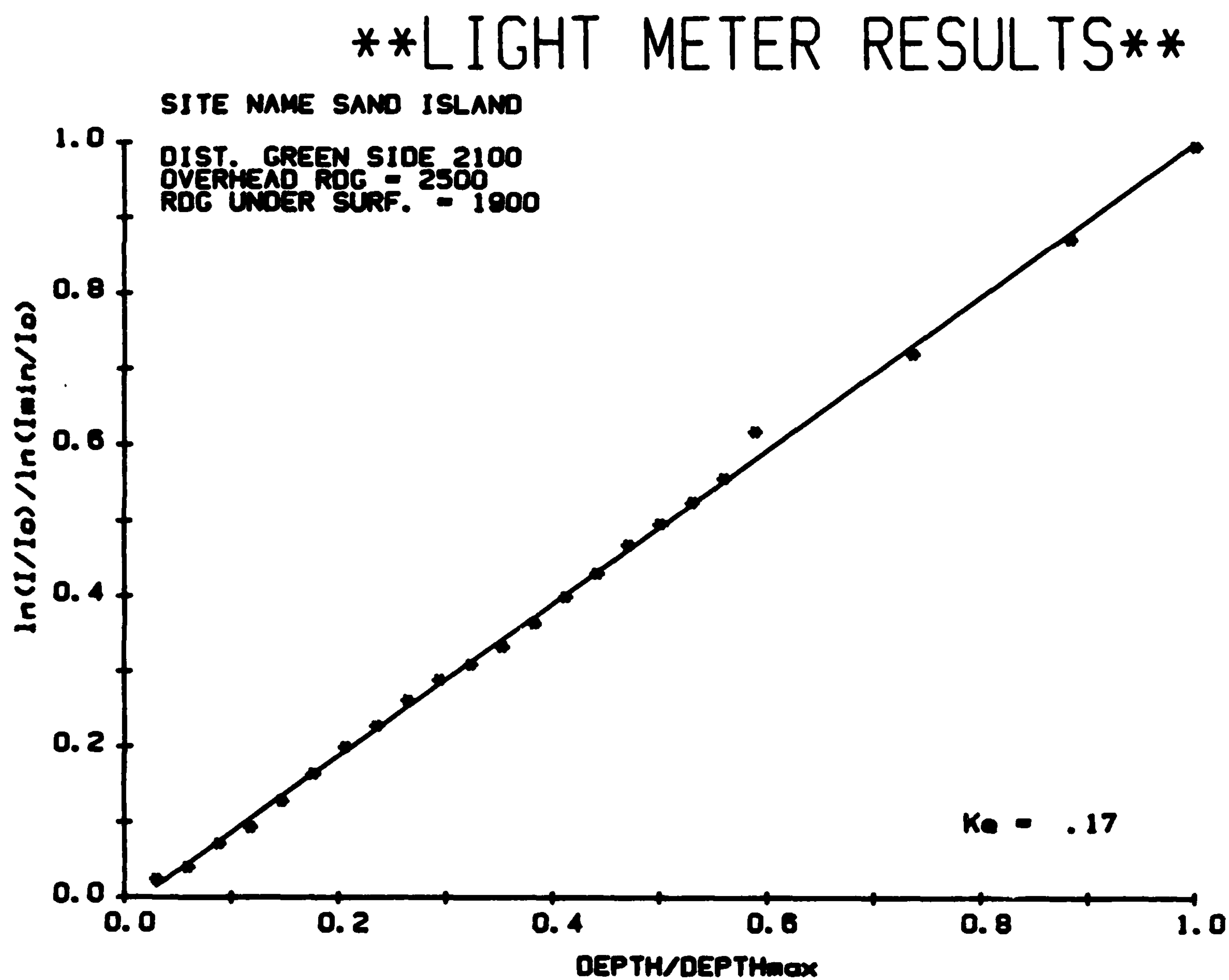

Figure 21. Normalized Light Extinction Profile After Vessel Passages

and 730 foot Paul H. Carnahan. These two vessels produced 1.2 foot and 1.4 foot drawdowns at the nearshore red side, respectively. For comparison the normalized light profile at this same location just <u>before</u> the passage of this pair of vessels is shown in Figure 22. Note that the light extinction coefficient increased only slightly after the passages and that neither plot shows significant data scatter from a single straight line relation. This can be interpreted as meaning that the degree of turbidity was about the same at all depths.

Samples were collected from a depth of 25 feet before and after the passages. They showed turbidities of 1.8 JTU and 2.0 JTU, respectively and confirmed the slight increase in the light extinction coefficient. Unfortunately, no further before and after events were monitored.

In all, 85 light profiles were measured. In general, they represent data gathered at the same locations at three different times--March, 1985 in the presence of a continuous ice cover, and again in May and June, 1985 with open water and normal vessel traffic. At most sites, profiles were developed in the shipping channel and in both the green and red side nearshores. A summary of the results is given in Table 3.

An inspection of Table 3 yields the following: the nearshore zones have more turbidity than the navigation channel with an ice cover and no traffic, and with open water and vessel passages; navigation channel turbidity was less in March than in May or June; in general, nearshore turbidity decreased with the removal of the ice cover; the turbidity in Lake Munuscong well away from the navigation channel was least with an ice cover, and most in June; the Lake Nicolet sites showed a slight decrease in turbidity upon removal of the ice cover; and the entry of the very turbid

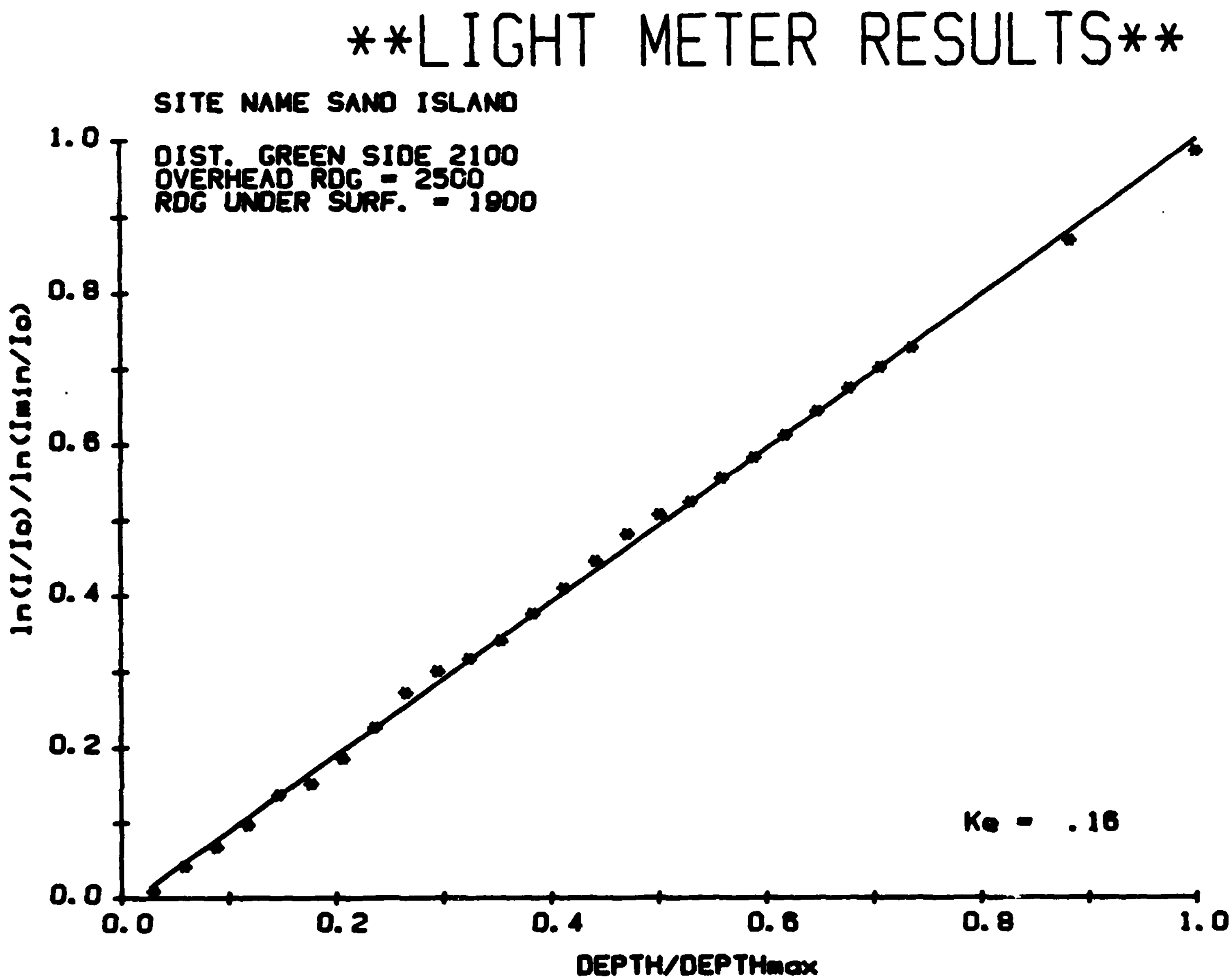

Figure 22. Normalized Light Extinction Profile Before Vessel Passages

Table 3. Summary of Light Extinction Coefficients

Date	Location	Dist. from green side, ft.	Total depth, ft	Ke ft^{-1}
3/19/85	R.V.	237	5	0.19
		437	19.4	0.09
3/17/85	S.I.	210	5	0.76
		2100	36	0.08
		2775	4	0.23
3/19/85	I.V.	215	15.5	0.16
		1000	34.6	0.11
		2068	5.4	0.16
3/17/85	E.C.D.	215	5	0.27
		515	35	0.10
3/38/85	E.C.D.	1130	28	0.10
		2130	8.2	0.17
		2930	4.2	0.30
3/17/85	W.C.D.	215	7.4	0.23
		665	9.5	0.23
3/17/85	M.I.	900	24	0.14
3/17/85	Munuscong	-1500	11	0.20
3/17/85	Nicolet	A	12	0.18
		B	7	0.25
		C	5.8	0.13
		D	5	0.21
3/17/85	Charlotte R.	200 ft. below brdg.	14.2	0.89
3/14/85	R.V.	1575	4	0.15
		900	36.2	0.11
		200	5.5	0.11
5/10/85	S.I.	210	5.5	0.45
		2100	34	0.16
		2775	4.5	0.15
		2100	34	0.17
5/10/85	I.V.	215	16.6	0.15
		1000	37	0.15
		1275	22	0.16
		2068	4.5	0.13
5/14/85	N.M.	300	3	0.11
		600	5.6	0.13
		2500	23	0.11
		4700	36.7	0.10
		5650	3.8	0.13
5/14/85	E.C.D.	215	6	0.15
		500	35.7	0.13
		1100	27.2	0.13
		2100	5	0.26
		2900	4.9	0.25
5/14/85	W.C.D.	1290	28.8	0.14
		695	29	0.14
		200	7.8	0.17

Table 3. Continued

Date	Location	Dist. from green side, ft.	Total depth, ft	Ke ft^{-1}
5/11/85	M.I.	900	34	0.21
		1175	6	0.48
5/11/85	Munuscong	-1500	10.7	0.26
5/10/85	Nicolet	A	12.3	0.17
		B	7.3	0.15
		C	8	0.16
		D	6	0.15
5/10/85	Charlotte r.	200ft below brdg.	14	1.26
		see note 1.	7	0.39
		see note 2.	4	0.22
6/2/85	R.V.	200	5.8	0.17
		900	34	0.13
		1575	4.1	0.13
6/2/85	S.I.	210	5.8	0.39
		2100	3.6	0.15
		2775	4.5	0.14
6/2/85	I.V.	215	17.5	0.18
		1000	37	0.18
		2068	5	0.20
6/2/85	N.M.	500	5	0.20
		2500	35	0.13
		4700	37	0.12
		5650	4	0.20
6/2/85	E.C.D.	215	6	0.21
		500	37	0.21
		2100	9.6	0.28
		2900	4.8	0.24
6/2/85	W.C.D.	200	9	0.18
		695	35	0.18
		1290	29	0.21
6/2/85	M.I.	200	7	0.53
		900	37	0.21
		1175	7	0.85
6/2/85	Munuscong	-1500	11	0.36
6/2/85	Nicolet	A	9.5	0.15
		B	8	0.13
		C	8	0.16
		D	5.3	0.16
6/2/85	Charlotte R.	200 below brdg.	8	1.17
		see note 1.	6.5	0.36
		see note 2.	5	0.24

Note 1. 500ft off green side, 1000ft downriver of mouth of Charlotte River

Note 2. 200ft off green side, 300ft upriver of mouth of charlotte River

Charlotte River is easily noticed on the green side of the St. Marys River by comparing readings above and below the mouth of the Charlotte River.

Turbidity Measurements

Prior to, and in conjunction with, the gathering of light profile data, turbidity measurements were made on water samples taken from various depths at the several sites. Sampling was performed in the field with a heavily weighted Van Dorn bottle, and laboratory determinations were made within 12 hours by means of Hach Model 1860-A turbidimeter reading in Jackson turbidity units (JTU's). Results and locations of November, 1984 sampling are given in Table 4. Findings from February, March, May, and June of 1985 are given in Appendix C--Observed Ice Thicknesses and Water Turbidities.

The results shown in Table 4 illustrate the combined background effects of vessel passages and normal wind-driven waves on the nearshore water where a clay bluff is present. These are very evident at Moon Island on November 2, 1984, and at Nine Mile on November 3, 1984. The increase in turbidity due to vessel passages alone can also be seen from the several sets of before-and-after data. They indicate that the temporary turbidity increase varies from little, if any, near the navigation channel to a maximum adjacent to the shores. This is due to the increasing turbulence as the water shoals, and to the direct attack of the surge on soil above the normal water level.

Table 4. Turbidity Measurements, November 1984

Date	Sample #	Location	Sample Depth Ft.	Condition	Turbidity JTU's
11/2/84	1	Moon Island Green Side Edge of Channel	2	Ambient	16
	2	Moon Island Green Side Edge of Channel	2	Ambient	16
	3	Moon Island Green Side Edge of Channel	2	Ambient	14
	4	Moon Island Green Side Edge of Channel	2	Ambient	15
	5	Moon Island Green Side Edge of Channel	2	Ambient	14
	6	Moon Island Green Side Edge of Channel	4	Ambient	15
	7	Moon Island Green Side Edge of Channel	4	Ambient	15
	8	Moon Island Green Side Edge of Channel	4	Ambient	12
	9	Moon Island Green Side Edge of Channel	4	Ambient	14
	10	Moon Island Green Side Edge of Channel	4	Ambient	14
	11	Moon Island Green Side Edge of Channel	6	Ambient	13
	12	Moon Island Green Side Edge of Channel	6	Ambient	13
	13	Moon Island Green Side Edge of Channel	6	Ambient	14
	14	Moon Island Green Side Edge of Channel	6	Ambient	15
	15	Moon Island Red Side 5' off shore	.5	Ambient	47
	16	Moon Island Green Side 5' off shore	.5	Ambient	380
	17	Moon Island Green Side 10' off shore	.5	Ambient	82
	18	Tap Water			3
11/3/84	19	Nine-Mile Red Side 5' off shore	.5	Ambient	260
	20	Nine-Mile Red Side 25' off shore	.5	Ambient	58
	21	Nine-Mile Red Side 50' off shore	.5	Ambient	29
	22	Sailors Creek	.5	Ambient	90
	23	Nine-Mile Green Side 5' off shore	2.5	Ambient	43
	24	Nine-Mile Green Side 5' off shore	1.5	Ambient	72
11/9/84	25	River View Green Side 6' off shore	.5	Ambient	6
	26	River View Green Side 40' off shore	.5	Ambient	5
	27	River View Red Side 6'	.5	Ambient	8
	28	River View Red Side 40'	.5	Ambient	6
	29	River View Mid Channel	5	Ambient	7
	30	River View Mid Channel	15	Ambient	4

Table 4. Continued

Date	Sample #	Location		Sample Depth Ft.	Condition	Turbidity JTU's
11/9/84	31	River View Mid Channel		25	Ambient	5
	32	River View Red Side	12' off shore	.5	After Passage-Gott	11
	33	River View Red Side	2' off shore	.5	After Passage-Gott	31
	34	River View Green Side	6' off shore	.5	After Passage-Gott	6
	35	River View Green Side	60' off shore	.5	After Passage-Gott	4
	36	River View Red Side	6' off shore	.5	Ambient	7
	37	River View Red Side	40' off shore	.5	Ambient	7
	38	River View Mid Channel		5	Ambient	6
	39	River View Mid Channel		15	Ambient	7
	40	River View Mid Channel		25	Ambient	7
	41	River View Green Side	6' off shore	.5	Ambient	6
	42	River View Green Side	40' off shore	.5	Ambient	3
	43	River View Green Side	6' off shore	.5	Ambient	7
	44	River View Green Side	40' off shore	.5	Ambient	7
11/8/84	45	River View	5' off shore	.5	Before Passage-Gott	6
	46	River View	5' off shore	.5	2 min. After Passage	8
	47	Sugar Island	50' off shore	.5	Before Passage-Richeliew	6
	48	Sugar Island	50' off shore	.5	After Passage	5
	49	Sugar Island	10' off shore	.5	Before Passage-Richeliew	18
	50	Sugar Island	10' off shore	.5	After Passage	23
11/10/84	51	River View Green Side	5' off shore	.5	Before Upbound Tadousac	10
	52	River View Green Side	60' off shore	.5	Before Upbound Tadousac	6
	53	River View Green Side	5' off shore	.5	Before Passage-Foy	7
	54	River View Green Side	5' off shore	.5	10 min After Passage-Foy	9
	55	River View Green Side	60' off shore	.5	Before Passage-Foy	7
	56	River View Green Side	60' off shore	.5	10 min After Passage-Foy	8
11/11/84	57	River View Green Side	5' off shore	.5	Before Passage-Bell River	10
	58	River View Green Side	5' off shore	.5	After Passage	13
	59	River View Green Side	60' off shore	.5	Before Passage-Bell River	7
	60	River View Green Side	60' off shore	.5	After Passage	8

Table 4. Continued

Date	Sample #	Location	Sample Depth Ft.	Condition	Turbidity JTU's
11/12/84	61	East Cell Dock Red Side 10' off shore	.5	Before-Selkirk Settler	11
	62	East Cell Dock Red Side 10' off shore	.5	After Passage	12,12,12
	63	East Cell Dock Red Side 75' off shore	.5	Before-Selkirk Settler	9
	64	East Cell Dock Red Side 75' off shore	.5	After Passage	8,8,8
11/14/84	65	Sand Island Green Side 55' off shore	.5	Before Passage-Algosoo	53,53
	66	Sand Island Green Side 55' off shore	.5	After Passage-Algosoo	50,50
	67	Sand Island Green Side 55' off shore	.5	At upsurge of Algosoo	50,50
	68	Sand Island Green Side 30' off shore	.5	Before Passage-Algosoo	22,22
	69	Sand Island Green Side 30' off shore	.5	After Passage-Algosoo	18,22
11/17/84	70	Island View Green Side 5' off shore	.5	Before Passage-Clarke	7,6
	72	Island View Green Side 5' off shore	.5	After Passage	7,6
	73	Island View Green Side 115' off shore	.5	Before Passage-Clarke	7,7
	74	Island View Green Side 115' off shore	.5	After Passage	6,6
	75	Island View Red Side 5' off shore	.5	Before Passage-Clarke	8,8
	76	Island View Red Side 5' off shore	.5	After Passage	7,8,8,8
	77	Island View Red Side 10' off shore	.5	Before Passage-Clarke	8,8
	78	Island View Red Side 10' off shore	.5	After Passage-Clarke	8,8
	78.a	Island View Mid Channel	.5	Before Clarke	11,8,8
	79	Island View Mid Channel	.5	After Passage	9,9
	80	Moon Island Mid Channel	10	Ambient	13,13
	81	Moon Island Mid Channel	25	Ambient	9,9
	82	South Moon Island 55' off shore	.5	Ambient	39,40
	82.a	Moon Island Green Side 5' off shore	.5	Ambient	25,24
	83	Moon Island Red Side 5' off shore	.5	Ambient	20,19
	84	East Cell Dock Mid Channel	10	Ambient	8,7
	85	East Cell Dock Mid Channel	25	Ambient	6,6
	86	East Cell Dock Green Side 5' off shore	.5	Ambient	7,7
	87	East Cell Dock Red Side 5' off shore	.5	Ambient	11,11
	88	West Cell Dock Mid Channel	10	Ambient	6,6
	89	West Cell Dock Mid Channel	25	Ambient	7,7
	90	West Cell Dock Red Side 5'	.5	Ambient	8,8

Table 4. Continued

Date	Sample #	Location	Sample Depth Ft.	Condition	Turbidity JTU's
11/17/84	91	West Cell Dock Green Side 5'	.5	Ambient	7,8
	92	Sand Island Mid Channel	10	Ambient	8,8
	93	Sand Island Mid Channel	25	Ambient	9,9
	94	Sand Island Green Side 5'	.5	Ambient	30,31
	95	Sand Island Red Side 5'	.5	Ambient	28,27

Ambient - Minimum of one hour since last vessel passage.

The turbidity measurements and the light profiles as well may allow general inferences as to the effects of extended season navigation, but in the absence of data in the presence of vessel passages with a continuous ice cover, no definitive statements can be made.

VESSEL-INDUCED ICE FORCES ON STRUCTURES

Ice forces on structures can be thought of as static or dynamic and can be grouped accordingly.

Static horizontal ice forces are those caused by thermal expansion or contraction of a continuous ice sheet and the cyclic horizontal growth of an ice sheet due to the process of sheet temperature shrinkage, cracking, intercrack water freezing, and subsequent sheet temperature expansion to a larger lateral size. The presence of a continuously used navigation track reduces or eliminates both of these situations since the sheet may expand channelward due to the very low lateral reaction available from the brash ice in the channel. No damage attributable to this cause has been observed along the St. Marys River during periods of winter vessel traffic.

Static vertical ice forces are those caused by very slow water level changes which cause the floating ice sheet to move upward or downward with respect to a fixed object to which it is frozen. The very slow water level changes under discussion are those associated with long-term seasonal water level changes and would be one-quarter inch per day or less. Due to the very low rate of loading, plastic yielding will occur within the ice or at the ice-structure interface at very low shear stresses. The result will be a very small vertical load transfer from the floating ice sheet to the fixed structure. This ice force mechanism is not relevant to winter navigation. Dynamic loadings are relevant, however, and are discussed below.

Dynamic Lateral Ice Forces

A typical ice cross-section to the channel centerline during

winter navigation consists of a) a narrow zone (10 to 50 feet wide) of shorefast ice resting on the river bottom and extending above the normal water level sufficiently far that it does not move during vessel passages, b) a floating ice sheet with one or more active continuous cracks more or less parallel to the shoreline, and c) the navigation track which is filled with floating brash ice to a depth of several feet. Typically the sheet separation at active cracks will vary between zero and four inches. The floating ice sheet does not develop a pattern of active or open cracks perpendicular to the shoreline as it does parallel to it. Normal winter vessel passages do not disturb the integrity of this sheet system, and the only horizontal movements observed have been short-term offshore-onshore oscillations of one inch or less and usually much less.

Observations , structures which are supported by the river bed have shown that the structure is completely within the zone of grounded ice or that an active crack parallel to the shoreline passes just channelward of the structure. The structures varied from navigation aids on cribs, to residential docks on gravity cribs or piles, to pile-supported boat houses, to pile supported piers at a commercial marina. In no instance was structural damage seen which was attributed to lateral ice movement during normal vessel passages. This was probably due to the characteristic relatively long uncracked ice sheet dimension parallel to the shore such that the entire sheet is not being loaded at the same time and is acting as a thin floating beam.

It has been observed, however, that on occasion ice-breaking activities by government vessels have disrupted this ice sheet which is normally continuous parallel to the shore. With aggressive ice breaking activities the entire floating sheet between the track and the shore may be broken into floating equidimensional

pans of 500 to 1,000 ft^2 in plan area. Once this has occurred, any lateral ice displacement due to passing vessels will be directly transmitted to the structures. For this situation a case-by-case analysis can be made by comparing the structure's lateral resistance to the maximum force which can be imposed by the ice sheet as shown below.

For stability: $P_{resisting} > (W_s)(I_t)(f_c)$

where $P_{resisting}$ = the structure's resistance before damage occurs, force

W_s = width of the structure in contact with the ice, length

I_t = ice thickness, length

f_c = compressive strength of the ice, stress.

The compressive strength of the ice used for this type of analysis varies from 100 to 400 psi depending on its temperature. However, even a crude analysis using an ice strength of 100 psi would demonstrate that residential docks and boat houses are not designed for this condition and that damage would be experienced before the ice failed by crushing.

Therefore, if ice-breaking activities are required which destroy the continuity of the nearshore ice sheet, it should be assumed that all undesigned or improperly designed structures residing in this nearshore zone will be damaged and their intended purpose impaired.

Dynamic Vertical Ice Forces

At a constant water level the thickening ice sheet will adhere to steel sheeting, timber cribs, and steel or timber

pilings which are present. Any water level change will therefore cause a vertical force to be transferred from the floating ice sheet to the structural member assuming that this member is not freely floating with the ice sheet. The net result depends on a number of variables such as the rate of loading (rate of water level change), ice thickness, ice strength, available resistance of the structural member in tension (a rising ice sheet) or compression (a falling ice sheet), and whether the pattern and spacing of the structural members are such that group action may occur. Experience has shown that for the range of ice thickness germain to this study, gravity structures such as rock-filled cribs are not affected by ice uplift and will not be considered further. The remainder of this section considers only more-or-less vertical piles which support piers and boat houses or act as spring piles.

Rate of loading for purposes here can be considered to be slow or rapid. A slow rate of loading would be that induced by a seasonal water level change, perhaps one-quarter inch per day. At this loading rate the ice would yield plastically and inconsequential loads would be transferred to piles. A rapid rate of loading would be associated with seiche oscillations and wind set-up on the connected Great Lake and by a vessel-induced drawdown/surge cycle.

For vessel passages the pattern of events is as follows:

> Vessel passages are frequent and the ice sheet fails in a circumference just outside the pile while the ice is thin.
>
> The ice sheet thickens and the pile's ice collar thickens, but an irregular narrow zone (an active crack) of water separates the two as this thin ice

connection is rebroken by every vessel passage.

At each vessel passage the pile feels compression as the floating ice sheet falls, and tension if a

following surge is present. During the tensile phase either the ice shears at the contact zone (the irregular active crack) or the pile moves upward with the ice sheet if the axial tension is treater than its uplift capacity.

If the pile does move upward, even if only an inch or so, it is likely that soil will move laterally into the void created at the pile's base by the upward movement. Therefore as the water level drops, the pile will not return to its previous height; rather it will have been jacked to a new equilibrium position.

Repeated vessel passages once the pile has been jacked upward will continue the jacking process until the pile's tip no longer encounters sufficient resistance during the downward movement portion of the cycle. By this time the pile may have moved several feet upward and its supported structure has been damaged.

This damage mechanism is quite common along the Great Lakes due to natural rapid water level fluctuations, and engineered pile-supported structures take these high tensile loads into account. Hodek and Doud (7) reported a 7,500 pound tensile load on an instrumented 14-inch diameter test pile at Ontonagon, Michigan with only an eight-inch ice thickness and an active crack around the pile. The water level rise and its rate which caused this load were 2.4 inches and 1.6 inches per minute, respectively.

While one cannot predict whether or not a particular pile along the St. Marys River will be jacked upward due to winter vessel traffic, the following statements can be made: Piles have been observed to jack in the absence of vessel traffic, many piles jacked during the demonstration program, and piles jetted or

driven by hand to a modest embedded length have very little axial tensile resistance.

Therefore, it should be assumed that all piles, unless properly engineered and installed, will be subjected to tensile loads greater than their capacities due to upward movement of the floating ice sheet caused by vessel passages, and they will eventually move upward.

HYDRAULIC EFFECTS OF ICE IN THE ST. MARYS RIVER SYSTEM

Very little field data exist to determine the actual influence of an ice cover on the discharge and water levels at various locations within the St. Marys River system. However, recent advances in our general understanding of the influence of an ice cover do allow for a qualitative analysis of the potential response of the natural system as well as the system influenced by winter navigation.

It has long been recognized that the stage-discharge relationship for various locations within a river system is dictated by control sections. Recent work by Santeford and Alger (11) has shown that ice induced effects on stage-discharge relationships can be subdivided into two broad categories: elevation controls, and resistance controls. When an ice cover forms on a river system, the stationary ice cover alters the size and resistance of the boundary in contact with the moving fluid. For the wide, shallow channel, the wetted perimeter is nearly doubled. Since the contact boundary between the underside of the ice and the flowing water is rougher than that which had existed between the water and air with the free water surface, the overall resistance to the flow must increase as the wetted perimeter increases. If the same discharge is to be maintained within the system both with and without an ice cover, one of several possible events must occur: the under-ice flow area must increase, the slope of the energy gradeline must increase, or a combination of both. To determine which of these cases will result, one must consider the control sections.

Elevation controls are those locations in a river system where the given conditions establish a fixed elevation of the free

water surface. For example, consider a weir or similar structure. For a given discharge, the "head" on the weir is fixed and consequently the elevation of the free water surface in the pool upstream of the weir is fixed. If an ice cover forms on the pool, then elevation of the free water surfaces a short distance upstream of the weir is fixed regardless of the thickness or roughness (i.e., resistance) of the ice in the pool upstream of the weir. As the ice in the pool thickens, the flow passageway under the ice diminishes. If the discharge is to be maintained, the under-ice velocity must increase. When the reach upstream of the weir is a true pool such that the flow velocity is nearly zero, the water surface will approach the horizontal. The addition of an ice cover increases the size of the contact boundary, but without a measurable velocity has no effect on headloss. Similarly, roughening the ice boundary, or increasing the thickness of the ice has no effect on water levels until such time that there is an appreciable velocity. In a natural river system a weir or "weir-like" feature often sets the depth vs. discharge relationship. However, in the river reach upstream of the weir there is a measurable velocity often termed as "approach velocity" for the weir. Since there is measurable velocity there is also a headloss and consequently a slope to the water surface. The weir sets the depth vs. discharge relationship while the approach velocity in conjunction with the channel resistance sets the headloss or slope of the water surface. The introduction of an ice cover alters the size of contact boundary and consequently increases the headloss. This, in turn, necessitates a steepening of the energy gradeline by increasing the elevation of the free water surface at some upstream location. The amount of the increase is a function of the submerged thickness of the ice (as it affects velocity) and the composite resistance to the flow caused by the combined effects of the streambed and ice surface.

Elevation controls are not limited to weirs or similar structures. The transition from open water to ice-covered conditions and the outlet of a lake are both further examples of elevation controls. The "outlet from a lake" is an important feature in determining the ice effects in the St. Marys system as well as other connecting waters in the Great Lakes network. Since the presence of an ice cover necessitates subcritical flow (i.e., a mild sloping outlet channel) there are only two possible situations which need to be considered: (1) the outlet channel produces a resistance control establishing a flow depth at the outlet from the lake between normal and critical or (2) there is a downstream elevation control causing the depth at the lake outlet to be greater than normal depth. With each of these cases, the development of an ice cover in the outlet channel will produce similar results (i.e., a decreased discharge and/or an increased energy slope), however, the sequence of events and magnitude of the effects are drastically different.

Consider the case where the lake is large and the outflow is set by resistance. When an ice cover forms on the lake there is no change in lake level. However, as the ice cover develops in the outlet channel the wetted perimeter and resistance both increase necessitating a much larger under-ice normal depth in the outlet channel if the current discharge is to be maintained. For the depth in the channel to increase, the lake level must also increase. Since that did not happen with freeze-up, the discharge from the lake can only decrease. With increasing time, the decreased discharge may produce increased storage in the lake which would cause both the lake level and discharge to increase with time. However, for any given lake level, the discharge in the outlet channel will be considerably less than with an ice cover than with an open water surface.

As the winter progresses the ice thickens in both the lake and the outlet channel. Assuming that the lake is relatively large and the outflow is relatively small, the thickening ice cover in the outlet channel produces a continually decreasing depth available to the flow reducing the discharge even further. Therefore, what may appear as a relatively stable lake and channel water levels will actually be occurring with an ever decreasing discharge as the ice cover in the channel continues to increase in thickness.

The condition just described adequately defines the effects of an ice cover on the discharge from the lower Great Lakes. The effects in the St. Marys River are somewhat more complex. First, the outflow from Lake Superior is a regulated quantity. The control structure, navigation locks, and two hydropower plants at Sault Ste. Marie regulate the discharge through the St. Marys River. With the discharge fixed, water levels within the system must adjust themselves to accommodate the ever changing conditions. The level of Lake Huron sets the lower elevation control about which the slope for the entire system will pivot. As the ice cover develops in the connecting channels between the larger lakes in the system, i.e. Lakes Nicolet, George and Munuscong, the discharge in the connecting channels is reduced allowing for increased storage in each of the lakes. This in turn causes the lake levels to rise. The difference in elevation between the various lakes and hence the energy slope is increased. Since the M-1 profiles that typically exist on the channels between the lakes have a very mild slope only slight changes in the relative elevations of the lakes are needed to produce the necessary percentage change in energy slope.

With winter navigation, the repeated breaking of the ice results in an increase in the unit resistance. In order to pass the

same discharge, the levels of Lakes Munuscong and Nicolet would have to rise and steepen the energy gradeline to overcome the increased resistance. However, as the levels on the American channel increased, a larger percentage of the total flow rate would be diverted into the Canadian channel, lessening the need for increased stages on the American side.

In an analysis of water levels and flows in the St. Marys River during winters with and witout significant number of vessel passages Alger (2) found that "...resistance to flow in an ice covered channel is increased with periodic disruption of the ice cover with attendant increases in water level..." His analysis also showed that for seasons without winter traffic the hydraulic resistance to flow (as measured by Manning's coefficient) was not affected by the severity of the season in freezing degree-days. Thus, it appears that the natural range of ice thicknesses from 1961 through 1971 and 1979 through 1981 was too small to affect the system hydraulically. When significant winter navigation was present (1972 through 1978) however, the additional ice which formed as a result of each vessel passage during subfreezing temperatures sufficiently changed the geometry and size of the flow channel as well as the roughness of the ice so that an increased resistance to flow was observed.

Because of the complexities of the system, the addition of an ice boom during the study period, and the lack of data it is currently impossible to predict with any degree of certainty the magnitude of increased water levels which would result from various winter navigation scenarios. With the available information, all that can be said is that with winter navigation the water level at all points within the St. Marys River system would be greater than they would be without winter navigation and the same discharge from Lake Superior.

DAMAGE EVALUATION FOR TWO FLEET MIXES

The utilization of the analytical model to determine the relative impacts of various fleet mixes and season extensions can best be demonstrated by working through the following two examples. Both examples use the same physical data, but have different fleet characteristics. Example 1 utilizes vessel traffic records provided for December 1978 thru February 1979, and example 2 uses a hypothetical traffic pattern.

The major engineering decisions required are the location to be evaluated, river level, river velocity, ice thickness as a function of time and position, vessel location in the channel, fleet mix and vessel draft as a function of travel direction.

The location chosen was the Nine Mile observation site. River velocity was chosen as 0.5 fps interpreted from the results of a Corps study (6). River level used was the river level at the time when the Nine Mile cross-section was sounded in late 1984.

The ice thickness pattern at various times during the winter was developed from published data and estimation. Fifteen years of ice thickness measurements (14) are available. Data from the Upper Lake Nicolet station were interpreted and averaged, the brash ice thickness in an assumed 400 feet wide track was estimated, and the ice area as a decimal part of the cross-section was computed for both the red and green sides. This information is shown below in Table 5.

Table 5. Ice Data Used at Nine Mile Site

Date	1/9	1/24	2/9	2/23
Ice thickness	4 1/4"	10 1/4"	14 3/4"	16 3/4"
Brash ice thickness	12"	24"	48"	72"
Avg. cross-section blockage	0.019	0.045	0.068	0.082
Red side blockage	0.021	0.048	0.078	0.099
Green side blockage	0.019	0.044	0.066	0.078

Published vessel dimensions by class (16) and estimated drafts for loaded and light conditions are shown below in Table 6.

Table 6. Vessel Dimensions by Class

Class	Length ft	Beam ft	Draft Loaded ft	Draft Light ft
5	627	60	24	19
6	676	70	25	20
7	728	60	26	21
8	782	70	26	21
9 & 10	858 & 1000	105	28	21

Each of these vessel classes was analyzed in each direction at the Nine Mile site at the speed limit of 14.7 fps under ice-free (prior to January 2) conditions and for each of the ice conditions shown in Table 5. It was assumed that from January 2 through February 15 all vessel traffic would use the upbound Middle Neebish channel and both the loaded and light drafts were considered in the upbound and downbound directions.

An example of the computer output is shown as Figure 23. It shows the predicted damage caused by a class 10 vessel fully loaded for both upbound and downbound passages, during the ice conditions between February 2 and February 15. Table 7 gives the complete results at the red side for the combinations of variables considered.

The damage matrix for the green side has not been presented since it does not show any damage potential changes from open water to winter conditions.

The relative damage potentials shown in Table 7 have been arbitrarily weighted by assigning numbers to the damage descriptions. Therefore once the matrix has been developed, comparative total damage for various fleet mixes and traffic patterns can be determined by summing the products of transits and vessel class in the appropriate categories for each scenariu and comparing the results.

Two traffic patterns are shown below along with their comparative damages. Table 8 shows the reported traffic from December 16, 1978 until the cessation of shipping in mid-February, 1979. The division of passages by direction was estimated since this breakdown was not available, and it was assumed that all upbound passages were made by vessels in ballast and all downbound vessels were loaded.

In parentheses are shown the products of nonzero damage rating from Table 7 and number of passages.

@@

NAME OF SECTION nine mile

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AREA ON GREEN SIDE OF UPBOUND VESSEL (sq. ft) = 93596
AREA ON RED SIDE OF UPBOUND VESSEL (sq. ft) = 26112
AREA ON GREEN SIDE OF DOWNBOUND VESSEL (sq. ft) = 93596
AREA ON RED SIDE OF DOWNBOUND VESSEL (sq. ft) = 26112
NEARSHORE GREEN - SUBMERGED WETLANDS
SOIL TYPE GREEN - MEDIUM SAND TO SILT
NEARSHORE RED - OPEN BLUFF OR ESCARPMENT
SOIL TYPE RED - MEDIUM SAND TO SILT
PERCENTAGE ICE on green side (decimal form) = .066
PERCENTAGE ICE on red side (decimal form) = .078
WIDTH OF WATER SURFACE (ft) = 5749
DISTANCE TO UPBOUND VESSEL from green side (ft) = 4550
DISTANCE TO DOWNBOUND VESSEL from green side (ft) = 4550
VESSEL BEAM (ft) = 105
VESSEL DRAFT (ft) = 28
RIVER VELOCITY (ft per sec.) = .5
UPBOUND VESSEL VELOCITY (ft per sec.) = 14.7
DOWNBOUND VESSEL VELOCITY (ft per sec.) = 14.7
DEPTH AT CENTER OF CHANNEL (ft) = 35

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DRAWDOWN OF UPBOUND VESSEL on the green side (ft) = 0.20
DRAWDOWN OF UPBOUND VESSEL on the red side (ft) = 0.89

CRITICAL DRAWDOWN on the green side (ft) = 5.05
CRITICAL DRAWDOWN on the red side (ft) = 4.60

PROBABLE DAMAGE GREEN SIDE = NONE TO LIGHT
PROBABLE DAMAGE RED SIDE = SEVERE

****

DRAWDOWN OF DOWNBOUND VESSEL on the green side (ft) = 0.16
DRAWDOWN OF DOWNBOUND VESSEL on the red side (ft) = 0.70

CRITICAL DRAWDOWN on the green side (ft) = 5.67
CRITICAL DRAWDOWN on the red side (ft) = 5.24

PROBABLE DAMAGE GREEN SIDE = NONE TO LIGHT
PROBABLE DAMAGE RED SIDE = MODERATE

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Figure 23. Effect of a Class 10 Vessel

Table 7. Damage Matrix for Nine Mile Site, Red Side.

	Draft, Ft.	Time Period 12/16-1/1	1/2-1/15	1/16-2/1	2/2-2/15	Vessel Class
Upbound	19	0	0	0	0	
	24	0	0	0	0	5
	20	0	0	0	0	
	25	0	0	1	1	6
	21	0	0	0	0	
	26	0	0	0	0	7
	21	0	0	0	0	
	26	0	1	1	1	8
	21	1	1	1	1	
	28	1	1	1	3	9 & 10
Downbound	19	0	0	0	0	
	24	0	0	0	0	5
	20	0	0	0	0	
	25	0	0	0	0	6
	21	0	0	0	0	
	26	0	0	0	0	7
	21	0	0	0	0	
	26	0	0	0	0	8
	21	0	1	1	1	
	28	0	1	1	1	9 & 10

Damage Rating: none to light 0
moderate 1
severe 3

Table 8. Reported Vessel Traffic, and Predicted Damage 1978-1979 Season

Class and Direction	Number of Passages 12/16-1/1	1/2-1/15	1/16-2/1	2/2-2/15
5 up	11	5	6	0
5 down	38	10	4	1
6 up	3	3	0	0
6 down	8	3	1	0
7 up	5	2	0	0
7 down	4	3	0	0
8 up	8	2	5	1
8 down	11	5	4	2
9 & 10 up	6 (6)	3 (3)	1 (1)	0
9 & 10 down	10	2 (2)	3 (3)	1 (1)
Damage	6	5	4	1

Table 9 shows a hypothetical fleet mix and the predicted relative damage. It also assumes that all upbound vessels are in ballast and all downbound vessels are loaded. The relation between number of vessels sailing and number of passages is that a vessel makes a round trip every six days.

Table 9. Hypothetical Vessel Traffic and Predicted Damage

Total Vessels Sailing	Time Interval 12/16-1/1	1/2-1/15	1/16-2/1	2/2-2/15
Class 8	21	9	6	6
Class 10	12	6	3	3
Class and Direction	**Number of Passages**			
8 up	57	21	17	14
8 down	58	21	17	14
10 up	34 (34)	14 (14)	9 (9)	7 (7)
10 down	34	14 (14)	8 (8)	7 (7)
Damage	34	28	17	14

This pair of examples predicts that the hypothetical fleet mix would cause more damage at the Nine Mile site than would the 1978-1979 winter traffic.

Similar damage matrices could be developed by the user to test the sensitivity of particular locations to winter vessel traffic, and each matrix can be used to evaluate a wide variety of fleet mix/traffic combinations.

SUMMARY AND CONCLUSIONS

An analytical model has been developed which relates the water level drawdown caused by a vessel to channel characteristics, vessel characteristics, river and vessel speed, lateral position of the vessel in the channel, and ice cover thickness. The model predicts that drawdown is extremely sensitive to vessel speed and lateral vessel position in the channel, and moderately sensitive to ice cover thickness. Field measurements under ice-free conditions confirmed the general validity of the model and also showed a useful relationship between vessel-induced drawdown and the accompanying surge.

It was shown that beyond some particular level of drawdown measurable net sediment transport occurs in an offshore direction. It was also shown that open-water vessel passages temporarily increase nearshore turbidity. A data base of light extinction coefficients and turbidity values has been developed and shows what is assumed to be the natural pattern in the absence of extended season navigation.

The direct ice-induced effects on the shoreline, and on ice bound structures as well, have been considered. The zone of grounded ice at the shoreline almost completely insulates the shore from erosion caused by the drawdown/surge pattern. As long as the ice sheet between the vessel track and the grounded shore ice is intact perpendicular to the channel, significant lateral ice forces will not be transmitted by vessels to structures. However, the vertical upward movement of the floating ice sheet due to vessel-induced surge will eventually damage the majority of jetted or hand-driven piles in the nearshore environment.

The use of the analytical model to determine relative damage for various fleet mixes was demonstrated for the Nine Mile study site. The damage matrix developed for this site indicates that, for most vessel classes considered, the nearshore damage per vessel passage during winter conditions can be greater than during ice-free transits.

RECOMMENDATIONS

Based on the findings of this study the following recommendations are made:

1. Determine the quality of the drawdown/surge predictions at vessel speeds near the normal speed limits.

2. Develop a predictive capability for nearshore water velocity as a function of vessel-induced drawdown.

3. Expand the data bases for light extinction coefficient and turbidity values so that the effects of natural seasonal variations and the effects of wind driven waves can be separated from vessel-induced ones.

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